Cranfield University

School of Industrial and Manufacturing Science

Integrated Waste Management Centre

PhD

2004

Peter P McHenry

The Strategic Evaluation of Technology Innovation Opportunities in Waste Strategy Planning

Supervisor: Dr Phil Longhurst

Date of Submission: June 2004

The thesis is submitted in partial fulfillment of the requirements for the Degree of Doctorate of Philosophy

ABSTRACT

Technology innovation is needed to support sustainable waste management systems and innovation should be viewed as a central focus of policy design. The difficulty is that policy is designed at a single point in time where as the environment and the processes of innovation are dynamic.

The research investigates the extent to which the design of European Union waste policy and its implementation in the UK stimulates the opportunity for technology innovation. The research investigates how understanding of the relationships between EU waste policy, the process of innovation and technology assessment technique affect the opportunity for technology innovation.

The research reviews the development of integrated waste management system models highlighting their limitation in evaluating waste technology options within the wider policy context in an uncertain environment over time. The review identifies their failure to consider the interaction between the financial, environmental, social and operational objectives of new technology. The research describes how failure to simulate system characteristics such as waste process operational demands/constraints, varying spatial resolutions, flexible system boundaries and the uncertain environment over time can affect the opportunity for technology innovation.

The research describes the development of a modelling tool addressing these limitations in SIMILE Process Simulation Modelling Software. The model uses the Bedfordshire sub-region of the UK as a case study mapping the flow of waste from generation to disposal. The model calculates a single cost function based on economic, environmental and social costs through, wherever feasible, attributing monetary values to all impacts of any technology.

Scenarios are modelled to investigate the extent to which EU waste policy and its implementation affects the opportunity for technology innovation. The model is used to investigate the extent to which relationships between the financial, environmental, social and operational objectives of technology create barriers to new technology.

The research identifies how the design, development and application of waste strategy assessment models can influence the opportunity for technology innovation. The research identifies how policy imposes additional cost burdens on the opportunity for technology innovation in the Bedfordshire region. The research concludes by suggesting how policy might be designed to stimulate and support technology innovation.

Acknowledgements

I would like to thank and acknowledge the help that Dr Phil Longhurst, Senior Lecturer, Cranfield University, has given me in producing this research in his capacity as my supervisor.

I thank and acknowledge the help of Dr Roger Seaton, Seaton Associates, Dr Martin Lowe, Shanks Waste Group and Dr Brian McIntosh, Cranfield University, who have helped steer the direction of the research.

I would like to thank and acknowledge my sponsors the Shanks Waste Group, EB Nationwide Ltd and the Economic and Social Research Council for funding the research.

Table of Contents

Chapter 1 – Research Aim, Objectives and Methodology

Chapter 2 – Literature Review

Chapter 3 – Processes within an Integrated Waste Management System

Chapter 6 – Scenario Options

Chapter 7 – Modelling Results

Chapter 8 – Modelling variation to the boundaries of the IWMS

Chapter 9 – Modelling variation to the Costing Process

Chapter 10 - Discussion

References

Appendix

Figures

Tables

Abbreviations

AAEV	Average Annual Equivalent Value
AHP	Analytical Hierarchy Process
AMT	Advanced Manufacturing Technology
BATNEEC	Best Available Technology Not Entailing Excessive Cost
BCC	Bedfordshire County Council
BPEO	Best Practical Environmental Option
CEC	Commission of the European Communities
CHP	Combined heat and power.
DCF	Discounted Cash Flow
Defra	Department for the Environment, Fisheries, Regions and Agriculture
DETR	The UK Department of the Environment, Transport and the Regions
DoE	The UK Department of the Environment
EC	European Commission
EfW	Energy from Waste
EU	European Union
HH	Household
HWRC	Household Waste Recycling Centre
IWMS	Integrated Waste Management System
ktpa	thousand tonnes per annum
LCA	Life Cycle Analysis
LCC	Life Cycle Costing
MBT	Mechanical Biological Treatment
MCA	Multi Criteria Analysis

MRF	Materials Recovery Facility
MSW	Municipal Solid Waste
NIMBY	Not In My BackYard
NFFO	Non-fossil fuels obligation
OECD	Organisation for Economic and Technical Change
ODPM	Office of the Deputy Prime Minister
p.a.	per annum
PFI	Private Finance Initiative
RDF	Refuse Derived Fuel
RTAB	Regional Technical Advisory Board
STPR	Social Time Preference Rate
SWMA	Strategy Waste Management Assessment
tpa	tonnes per week
WCA	Waste Collection Authority
WCED	World Commission on Environment and Development
WDA	Waste Disposal Authority
WEEE	Waste electrical and electronic equipment
WISARD	Waste Integrated Systems Assessment for Recovery and Disposal

Chapter One – Research Aim, Objectives and Methodology

It is widely accepted that technology innovation is needed to support sustainable development (WECD, 1987, CEC, 2002) and innovation should be a central and fully integrated issue when designing, developing and implementing policy (CEC, 2001). The UK waste sector is being challenged to be more innovative in its development of waste strategies as the growth in European Union (EU) environmental legislation places an increasing burden on the waste sector in the UK. The research investigates the extent to which the design and implementation of such policy affects the pathway of opportunity for new technology needed to support the sustainable management of waste in the UK.

1.1 Introduction - The Evolution of European Union Waste Policy

Haigh (1997) identifies three phases in the development of European Union (EU) waste policy since 1975 (See Appendix 1 – A Review of European Union Waste Policy):

- 1975-85 - A focus on end-of-pipe solutions e.g. the setting of emission standards.
- 1986-96 - A more preventative approach e.g. the elimination of harmful substances.
- 1997 to present - An increase in producer responsibility e.g. through the development of waste stream legislation such as the Packaging Directive.

The 6th EU Environment Action Programme. 'Environment 2010: Our future, our choice', 2001 – 2010 outlines current EU policy for the sustainable management of resources and waste. EU waste policy is broadly based on four key principles (EFIEA, 2003):

- Prevention – reduction of waste at source.
- Producer responsibility and polluter pays – those who produce waste should pay for their actions.
- Precautionary principle – the potential problems should be anticipated.
- Proximity principle – waste should be disposed of as near to its source as possible.

In an interview, Otto Linher of the European Commission, 23 April 2003 (EFIEA, 2003) he outlined that future policy will shift towards Integrated Product Policy (IPP); this being where policy is based upon the lifecycle of products no matter the source with targets set for the reuse and recycling of specific materials within the wider Municipal Solid Waste stream.

Table 1.1 outlines current Municipal Solid Waste legislation stemming from this evolution of policy:

Table 1.1 - European Union Directives affecting Municipal Solid Waste

Council Directive 75/442/EEC of 15 July 1975 on Waste, last amended by Council Directive 96/59/EC of 16 September 1996.

Deadline for implementation of last amended Directive 16.03.1998

Member states must prohibit the uncontrolled discarding, discharge and disposal of waste. They shall promote the prevention, recycling and conversion of waste with a view to their reuse. An integrated, adequate network of disposal installations (taking into account of the best available technologies) should enable individual member states to dispose of its waste. Companies or establishments treating, storing or dumping waste must obtain appropriate authorisation from a competent authority. The cost of the disposal must be borne by the producer who has generated the waste in accordance with the polluter 'pays principle', or holder if waste has transferred ownership. Individual member states should draw up management plans governing waste strategy.

Council Directive 96/61/EC of 24 September 1996 on Integrated Pollution Prevention and Control

It was designed to bring an integrated control to pollution control with all the main polluting processes regulated through one permitting process. With an emphasis on pollution prevention, it states that waste production is avoided and where waste is produced it is recovered, or where that is technically and economically impossible it is disposed of while avoiding or reducing the impact on the environment. It favours the adoption of preventative innovative clean technologies based upon the Best Practicable Environment Option (BPEO) for emissions, with a consideration of the Best Available Techniques Not Entailing Excessive Cost (BATNEEC) and minimisation of waste.

Council Directive 99/31/EC of 26 April 1999 on the landfill of waste.

Deadline for implementation 16.07.2001

The objective is to prevent or reduce as far as possible negative effects on the environment from the landfilling of waste, by introducing stringent technical requirements for waste and landfills. It challenges the approach of the waste management sector in EU member countries by imposing three key demands:

i. Targets for the reduction in the landfill of biodegradable waste
    - To reduce the volume landfilled to 75% of 1995 figures by 2010
    - To reduce the volume landfilled to 50% of 1995 figures by 2013
    - To reduce the volume landfilled to 35% of 1995 figures by 2020

ii. The banning of co-disposal of hazardous and non-hazardous wastes, with requirement for separate landfills for hazardous, non-hazardous and inert wastes.

iii. The requirement to pre-treat all waste prior to landfill (the directive defines treatment as the physical, thermal, chemical or biological process, including sorting, that change the characteristics of the waste in order to reduce its volume or hazardous nature, facilitate its handling or enhance recovery).

Directive 2000/76/EC of the European Parliament and of the Council of 4 December 2000 on the incineration of waste.

Deadline for implementation is 28 December 2005 for existing plants and 28 December 2002 for new plants.

It is intended to incorporate the technical progress made on monitoring incineration process emissions into existing legislation to reduce pollution and compliance to limit values for the emissions especially dioxins, mercury and dusts arising from waste incineration. The directive applies to both waste incineration plants and co-incineration plants where waste is being used to produce energy. To guarantee waste incineration plants are required to keep the incineration temperature at least 850 degrees Celsius for at least two seconds. It introduces levels of dioxins as a new parameter for discharges into water and stipulates that residues from the combustion process must be minimised, harmless and recycled where appropriate.

Table 1.1 - European Union Directives affecting Municipal Solid Waste - Continued

Council Directive 94/62/EC of 15 December 1994 on packaging and packaging waste, last amended 7 December 2001.
It covers all packaging and packaging waste in the Community. It aims to prevent or reduce the environmental impact caused by packaging/packaging waste, and ensure the functioning of a market for recycled materials. It sets targets for the prevention, the re-use, and the recycling or recovery of packaging waste. These targets include recovering 50-60% and recycling between 25-45% of packaging waste by mid-2006. The amended directive lays down greater targets to be met by 30 June 2006, these include to recover between 60-75% and recycle between 55-70%. It introduces specific recycling targets for materials: 60% for glass, 55% for paper and cardboard, 50% for metals and 20% for plastics.
Council Directive 2002/96/EC on waste electrical and electronic equipment last amended 10 April 2002.
Objective to promote the re-use, recycling and forms of recovery of electrical and electronic waste in order to reduce the quantity of such waste to be eliminated and improve the environmental performance in the treatment of such waste. The proposal applies to several categories of electrical and electronic equipment including household appliances e.g. fridges. Member states must set up collection systems under which distributors of electrical equipment can return such equipment free of charge from private households. By 31 December 2008 a minimum rate of four kilograms per year per inhabitant of separated electrical and electronic equipment must be recovered.
Animal by-products Act (EC) No 1774/2002
Identifies rules concerning animal by-products not intended for human consumption and has to be applied to all member states from May 1 2003. It addresses inappropriate processing standards and the use of rendered products (that were believed to be the reason for the outbreaks of Bovine Sponiform Encephalophathy (BSE) and Foot & Mouth Disease). It categorises animal by-products and wastes into three groups based on associated risk with defined treatment and utilisation processes. There is widespread confusion surrounding the introduction of the legislation in the UK (Recycling and Waste World, July 2003).

1.2 Limitations of European Union Waste Policy

Various limitations and weaknesses in EU Waste policy have been identified (EFIEA, 2003, Haigh, 2003, Lowe, 2002). Some examples of these weaknesses are described below:

- The definition of waste – The lack of clarification of the definition of waste creates confusion when evaluating the performance of waste management systems. When does a material transfer from being a resource into a waste? Does it depend on the economic value of the material or the processes that generate the material? For example in a case law in Finland, April 2002 (Case C-9/00, Palin Granit Oy v. Vehmassalon) in a dispute as to whether surplus stone from a quarry was waste or not, it was identified that the surplus stone is waste despite its economic value (EFIEA, 2003). The European Court of Justice identified that there is no decisive test to determine whether or not a material is waste.
- The definition of treatment technologies – Uncertainty over the clarification and definition of treatment technologies can be exploited as a weakness in waste management systems (EFIEA, 2003). The lack of clarification is exploited in some countries to avoid the additional costs that compliance to waste legislation often incurs. For example, waste exported for recovery is often subject to less administration than waste for disposal. Many waste producers in the EU export

increasing amounts of waste to recovery technologies to avoid national legislation relating to the disposal of waste that is often stricter and more costly (EFIEA, 2003).

- Unfounded targets - Environmental legislation in recent years has been dominated by the setting of targets e.g. for recycling, for the diversion of biodegradable waste from landfill etc. The difficulty is that these targets have not been justified (Lowe, 2002). What is the optimum level of recycling? Should targets be regularly increased? Is the cost of increasing the recycling rate from 20 to 30% the same as increasing the recycling rate from 50 to 60%? Is the environmental cost of sorting material, the transportation of recovered material to a reprocessing facility and the reprocessing of material less than the environmental benefits of recycling the material?
- Single waste stream legislation - As described in Table 1.1 the WEEE Directive, the Packaging Directive and the Landfill Directive all set individual waste stream targets. Though intended as a mechanism to drive technology to improve waste management performance, to what extent does the setting of single waste stream policy actually act as a barrier to new, more efficient technology? For example the banning of the disposal of fridges to landfill under the WEEE Directive has created 'Fridge Mountains' throughout the UK as the industry struggles to find financially and environmentally acceptable technology for their disposal (Seaton et al., 2003). This has led to additional environmental problems resulting from fires such as at the Britannia Plc fridge recycling depots in Chadderton, Oldham, 2003 (ENDS Report, 2004).
- Shifting legislative boundaries - The shifting boundaries of legislation create short-term planning rather than long-term strategy planning. The UK waste industry is a reactive industry dominated by short-term planning with technology often designed to meet the next 'target' only (Lowe, 2002). To achieve the 'sustainable development' objectives of the 6th EU Action Programme and sustain technology performance in an uncertain environment, long-term planning or adaptive technology strategies are needed.
- Technology assessment criteria – Policy dictates that technology needs to meet BATNEEC and BPEO requirements (as identified in the IPPC directive) but these are 'weak' criteria for the evaluation of technology. Jeffrey (1992) argues that to develop technology with the ability to sustain performance in an uncertain environment over time technology characteristics such as flexibility, adaptability and resilience should be sought when evaluating technology options. These characteristics enhance a technology and system's ability to sustain performance in an uncertain environment such as an integrated waste management system.
- Conflict between different policy areas – Waste policy is often in conflict with other policy areas. For example, environmental legislation is intended to drive recycling but this increases the transportation of waste. As recycling increases local markets for recovered materials will become saturated with recovered material needing to be transported to markets further away. Thus increasing recycling can lead to increased transportation of waste with the resultant increase in environmental pollution associated with transportation. It is argued that environmental legislation is merely transferring the environmental pollution from waste to other areas such as transportation (Downer, 2003).
- Lack of Spatial Awareness - Policy formulated at a macro spatial level (i.e. EU) is implemented at a meso spatial level (i.e. nationally) and strategy planning

decisions for new technology are based upon micro spatial level (i.e. local) conditions. A weakness of EU waste policy is that it fails to account for localised conditions that can affect the performance of waste management systems and the opportunity for new technology. For example policy is aimed at reducing the use of landfill as a disposal technology for waste yet in some member states such as the UK landfill, due to favourable economic and geological conditions, has long been the most favoured waste disposal option.

- Temporality of Policy – Policy is formulated at a single point in time, the future is uncertain, future resources, processing technologies, transport and market costs are unpredictable. Policy can be a barrier to new technology as technology develops faster than policy that is often hampered by excessive bureaucracy. For example, advanced thermal treatment technology such as pyrolysis is operational in other areas of the world such as Japan, but given the bureaucracy associated with the incineration of waste in the EU, the technology is not yet operational.

Given these limitations in policy design and implementation the opportunity for technology innovation in the waste sector in the EU is hampered by a complicated decision process when evaluating options within an integrated waste management system. The research will show that these limitations in policy affect the opportunity for new technology and the cost of waste strategies.

1.3 The Implementation of European Union Waste Policy in the UK

In 2000/1 approximately 28 million tonnes of Municipal Solid Waste (MSW) was produced in England with almost 80% sent to landfill and just 12% recycled (Environment Agency, 2003). The growth in environmental legislation relating to the waste industry is challenging the UK Waste industry to reduce its reliance on landfill as a waste disposal technology.

In the UK, municipal solid waste management is primarily the responsibility of local government and is enacted according to the administrative structure in place (i.e. either on a county, metropolitan, or unitary authority basis, see Table 1.2). Within the shire counties, District Councils are responsible for the collection of MSW called Waste Collection Authorities (WCA's). County Councils are responsible for the treatment and disposal of MSW, these are known as Waste Disposal Authorities (WDA's).

The operational aspects of waste management are largely contracted out to the private sector. This contracting out of services is often partly financed through the Private Finance Initiative, discussed later in the chapter. In recent years the private sector has seen a takeover of smaller waste companies by larger international firms that currently dominate the UK Waste industry. The leading UK Waste companies include the Shanks Group, Biffa Waste, Cory Environmental and Sita. The fragmentation of responsibility of the waste strategy creates complication when evaluating waste management systems (Lowe, 2002). The research will show that through integration of local authorities and the development of regional strategies costs associated with waste management can be reduced.

Table 1.2 Waste planning, strategy and implementation responsibilities in England. (Adapted from Environment Agency, 2001 and ESTU, 2002.)

Spatial Planning or Policy Body	Responsibilities
Regional Planning Body (RPB)	To establish land-use planning guidance for the region.
Regional Technical Advisory Body (RTAB)	Collect information on waste management within the region. Produce a recommendation for the Regional Planning Body.
County and Unitary Planning Authorities	To set out land-use policies for their areas within the framework set by RPB and Structure Plans. Preparation of local waste plans identifying areas where facilities could be sited. Granting and enforcement of planning permission for new facilities.
Districts & Unitary Authorities – Waste Collection Authoritites	To let contracts in accordance with national waste strategy for the collection, sorting and recycling of municipal waste. Will implement strategies to include technology such as material recovery facilities and composting plants.
County Councils in England, District Councils in Wales and Scotland, and Unitary Authorities – Waste Disposal Authorities	To let contracts for the disposal of waste collected by the Waste Collection Authorities in accordance with national waste strategy.

The UK government outlined the strategy for implementing the numerous environmental directives (described in Table 1.1) in 'Waste Strategy 2000' (DETR, 2000a). 'Waste Strategy 2000' identifies a two step approach:

i. Tackle the amount of waste produced by breaking the link between economic growth and waste production.
ii. Put waste to good use through substantial increases in re-use, recycling, composting and the recovery of energy.

'Waste Strategy 2000' promotes various methods for achieving the EU legislative goals, including:

1. The Waste Recycling Action Program (WRAP) – funded through the landfill tax credit scheme it aims to promote the re-use and recycling of waste e.g. paper, glass, plastics and wood. WRAP seeks to identify a range of technologies for single waste material strategies.

2. An emphasis on Reuse and Recovery in waste management strategies.

3. Recycling Targets – targets and goals for improved waste management e.g.
   - To recover value from 40% of municipal waste by 2005
   - To recover value from 45% of municipal waste by 2010
   - To recover value from 67% of municipal waste by 2015

   Recover means obtaining value from waste through one of the following means i.e. recycling, composting, other forms of material recovery e.g. anaerobic digestion, or energy recovery.

   Statutory targets for local authorities
   - To recycle and compost 17% by 2003 and 25% by 2005/6.
   - To recycle 30% by 2010 and 33% by 2015.

4. The promotion of a cyclic approach to consumption and production process. A linear approach is typified by raw materials being processed into a product, leading to waste generation. To develop cyclical systems there needs to be:
   - Greater provision of single material waste streams – through separation at source or sorting.
   - Greater reprocessing capacity, to turn waste materials into new inputs.
   - More use of recycled (or secondary) materials in the production process.

5. Greater waste stream producer responsibility as identified and a requisite of the WEEE directive.

6. The Landfill Tax Escalator – the landfill tax is a tax applied to household and other active waste disposed to a licensed landfill site. From 1st April 2003 it increased from £13 per tonne to £14 per tonne. It will increase by a further £1 to £15 per tonne from 1st April 2004. From 2005-2006 it will increase by £3 per tonne per annum towards a rate of £35 per tonne (HM Treasury Budget, 2003).

7. Pollution Prevention and Control as identified by the IPPC directive, with an emphasis on prevention and minimisation of waste.

8. Best Practical Environmental Option (BPEO) - the development of the Environment Agency's Life Cycle decision support tool called WISARD that is often used to help suggest the BPEO to waste strategy planners.

9. Best Value Initiative – local councils have to set 5 yearly targets for improvement in waste management performance.

10. The UK promotes a regional format for strategy planning where local authorities are encouraged to formulate regional strategy.

11. Private Finance Initiative (PFI) – PFI is a way of funding waste strategy services between Private and Public organisations. In Private Finance Initiatives the public sector purchases services from the private sector. The private sector is responsible for the investment of capital with payment from the public sector dependant on achieving various quality standards of service. Public Private Partnerships are aimed at negotiating deals that offer a potential return to private sector investment dependant on their ability to meet the quality standards identified by the public

sector. The potential benefit is that, through improving the service standards of the private sector, quality standards are improved and in return the profit margins for the private sector are increased through improved efficiency of performance.

In 1999 Herefordshire and Worcestershire County Council signed the first waste management contract under the PFI scheme. The contract is anticipated to be worth in excess of £500m over its 25year term. The attractiveness of PFI to the waste sector is not just that it can access capital investment to improve services, it offers the opportunity for significant risk transfer. Risks associated with waste strategy planning are due to the uncertainty over waste generation, market prices, transport costs, inflation and interest rates etc. Within a PFI contract risk should be allocated to whom is able to manage it at least cost. If the private sector is forced to take all responsibilities of risk, the private sector will simply increase its price for services. Alternatively if the risks are shared or based upon some profit-related scheme the price for services might be reduced and the value of money maintained. Here the value of money will relate to the performance of the private sector to provide quality in its service. The main benefit of risk transfer is that it generates incentives for the private sector to provide services cost effectively and to a higher quality. Rather than performed to minimum required standards of recycling etc.

1.4 The Process of Technology Innovation

It is important to identify a definition for technology innovation given the different concepts of innovation. Dosi 1988 defined innovation as the search for and discovery, experimentation, development, initiation and adoption of new products, new processes and new organisational set-ups. Trott 1998 defined innovation not as a linear process but a system approach of multidirectional linkages in the transfer of information. The OECD 'Frascati Manual' 1993 defines technological innovation as the transformation of an idea into a new or improved saleable product or operational process. It thus consists of all those scientific, technological, commercial and financial steps necessary for the successful development and marketing of new or improved manufactured products, the commercial use of new or improved processes and equipment or the introduction of a new approach to a social service.

The term 'Technology Innovation' or 'New Technology' within this thesis incorporates the broader definition in that it is the development of knowledge both practical and physical, and its successful implementation.

As the concept of innovation has evolved, different pathways to stimulate innovation have emerged (CEC, 2001). In the 1980's innovation was viewed as a product of a linear sequence of events emerging from increased research and development activity. In the 1990's it was identified that innovation could emerge as a result of technology transfer and the sharing of knowledge. Post 2000 the role of innovation as a central focus when planning policy has emerged (CEC, 2002).

Through varying the process of integration of technology, barriers to technology innovation can be overcome and pathways to stimulate innovation enhanced. For example technology implemented on an incremental basis rather than dramatically can reduce uncertainty and risk associated with the technology. The process of integration includes issues such as the different concepts of innovation, the timing of technology change, the rate of change and the aggregation of sequences of technology change.

1.5 Research Aim, Objectives and Methodology

It is predicted that up to 4,000 additional waste management facilities will be needed in the UK by 2020 as landfill resource diminishes (Wastes Management, 2004). European Union waste policy and legislation is designed to stimulate the development of new technology needed to drive the sustainable management of waste. The difficulty is the inefficiency of policy to drive technology innovation as policy is developed at a single point in time where as technology innovation and the environment are dynamic. For example, in the UK waste sector though it is widely accepted that to achieve sustainable waste management technology innovation is needed, landfill technology has dominated the management of waste with over 85% deposited in landfill sites over the last 20 years (Environment Agency, 2001). Policy intended to stimulate innovation can become a constraint on the opportunity for innovation as it fails to allow flexibility to adapt to the evolving conditions over time.

For example policy has adopted a top down approach through the setting of goals and targets that the waste management sector must work towards. The difficulty is that the sector is more complex with operational, economic, environmental and social issues affecting waste management strategies. Through designing waste policy with a top down approach policy has applied constraints on the opportunity for new technology needed to drive sustainable waste management systems. For example recycling technologies have become increasingly widespread in the UK as the sector seeks to attain various recycling targets. These may not necessarily be the best technology option for the management of waste as it is argued that recycling can merely transfer the environmental impact of waste to transportation pollution (Downer, 2003, NSCA, 2002). Through developing waste strategy based upon such single focused policy, systems become highly dependant on key variables such as markets for recycled materials. A limitation of designing policy in this way is that a system's performance is more sensitive to uncertainty over time and the opportunity for technology innovation is constrained by the inflexibility of policy. The research will show the weakness of developing waste strategies on single waste streams such as the recycling of paper due to the uncertainty in the market price for paper. By constraining policy to specific objectives such as paper recycling mountains of unwanted recycled paper can ultimately be disposed to landfill after the costly recycling process has been completed, if the uncertain market becomes saturated.

1.5.1 Research Aim

Research Hypothesis:
If integrated waste management systems are not constrained by EU waste policy and its implementation in the UK, are costs of technology innovation in waste strategies reduced? Without the constraints of policy is the opportunity for technology innovation and sustainable waste management systems improved?

This research aims to investigate the extent to which waste policy design and its implementation in the UK influences the opportunity for technology innovation in the UK waste sector. To evaluate the influence of policy in stimulating the opportunity for technology innovation, an evaluation technique is needed that allows policy and technology assessment within an integrated waste management system over time.

The research will address specific questions and challenges that the UK waste sector faces:

1. How will the sector deal with the reduced availability of landfill capacity? What impact will this have on the cost of waste strategy?
2. What sensitivity to uncertainty is there to developing strategies based upon the policy of single material recycling targets?
3. Does the fragmentation and lack of regional integration created by the implementation of policy affect the cost of waste strategies?
4. How do the different levels of policy framework affect strategy performance and opportunity for technology innovation?

1.5.2 Research Objectives

The research investigates the relationships between EU waste policy, technology assessment and opportunity for innovation. The research investigates the extent to which:

- Policy influences the design of integrated waste management systems.
- The design of the integrated waste management system influences the opportunity for technology innovation.
- The opportunity for technology innovation is influenced by the selection of the technology assessment process.

1.5.3 Methodology

The opportunity for new technology is estimated through identifying the cost of developing technology needed to comply to EU waste policy. An assessment technique is needed that enables assessment of the Integrated Waste Management System (IWMS) and new technology over time. To achieve such a technique an understanding of the factors that influence an IWMS is needed.

The research uses the Municipal Solid Waste (MSW) generation in Bedfordshire as a case study, describing the development of a modelling tool as a mechanism to assess the performance of the integrated waste management system (IWMS) over time. The approach displays a shift from established IWMS models that often evaluate technology in isolation and fail to consider the dynamic environment. Through understanding and consideration of the wider policy design an assessment as to its ability to stimulate and enhance technology innovation can be gained.

The model is used to simulate the complicated waste management strategy in the Bedfordshire sub-region of the UK. The model maps the flow of waste from generation through treatment and recycling technology to disposal. It calculates a single cost function based on economic, environmental and social costs through, wherever feasible, attributing monetary values to all impacts of any technology. Using the single cost function the model identifies the performance of the IWMS. The tool enables exploration of varying waste system performance over time.

The thesis concludes by identifying how policy can be better designed to stimulate technology innovation in the UK waste industry.

1.6 Structure of the Thesis

Chapter 2 identifies the range of factors that influence the performance of an integrated waste management system identifying that any evaluation method needs to consider a range of economic, environmental and social factors. The chapter identifies that to achieve a long-term and analytically robust appraisal the interaction between financial and human socio-economic objectives need to be considered. The chapter reviews waste management system models identifying their limitations to simulate these complicated relationships.

Chapter 3 describes waste process technologies in greater detail identifying operational process constraints of waste technology that affect the performance of waste management systems. In an IWMS operational issues such as the changing characteristics of waste, the knock on effects of one process on another and the changes in waste handling properties need to be considered when evaluating the opportunity for new technology. Their lack of consideration in established IWMS assessment models is identified as a weakness of such evaluation techniques.

Chapter 4 describes the design of an IWMS evaluation model identifying the compromises needed between model development and the ability to simulate the complicated relationships identified in Chapters 2 and 3. The chapter reviews potential evaluation approaches such as waste stream, waste material or technology process assessment that have emerged in parallel to the evolution of EU waste policy. The chapter identifies the limitations of adopting each approach and how it can constrain the opportunity for new technology.

Chapter 5 describes the development of the model in the selected Simile Process Simulation modelling software. The chapter reviews the trade-off between the ability to simulate a complicated integrated waste management system and simplicity to support model development. The chapter identifies how the trade-off in the model design affects the opportunity to evaluate technology innovation. The chapter discusses the impact of generic modelling issues such as model calibration, validation and data availability etc.

Chapter 6 describes the identification of technology options and scenarios to model. The scenarios to model are designed to investigate the extent to which EU waste policy and its implementation in the UK constrains the opportunity for new technology. The opportunity for new technology is measured by identifying the cost of developing new technology to comply too EU waste policy within these conditions. The scenarios selected for modelling are identified to investigate the research objectives i.e. to investigate the extent to which EU waste policy, the process of innovation and the technology assessment technique can limit the opportunity for technology innovation.

Chapter 7 describes the modelling results identifying the constraints of waste policy on the opportunity for new technology in the Bedfordshire sub-region of the UK. The results are analysed to investigate the extent to which the barriers to new technology created by the relationships between the financial and strategic objectives of policy, as identified in Chapters 2, 3 and 4, affect the opportunity for new technology. The ability to overcome these barriers provides an assessment as to the extent to which the opportunity for innovation is constrained by the limitations in policy design and implementation.

Chapter 8 investigates the impact of varying the spatial resolution of assessment, the boundaries of the system and uncertainty on the opportunity for new technology. The results identify the extent to which EU waste policy and the implementation of policy in the UK affects the design of the IWMS. The chapter investigates the extent to which this impact on the design of the IWMS affects the opportunity for new technology by varying the cost of compliance to EU waste policy.

Chapter 9 investigates the extent to which the technology assessment technique affects the opportunity for new technology. The chapter compares the cost calculation process with an alternative technique where costs are distributed over the lifecycle of the assessment period rather than at single points in time. The comparison of results provides a sensitivity analysis of the results and is used to investigate the timing of technology change on IWMS performance and the opportunity for new technology. It provides assessment as to how a different accounting technique can be used to affect the process of implementation of innovation.

Chapter 10 describes the significance of the work in the wider context discussing the impact of the work when considering how future EU waste policy and its implementation might develop. It suggests how policy might be designed to stimulate technology innovation through incorporating a more dynamic approach and understanding of the process of innovation. The chapter discusses the importance of considering the interaction between the design of EU waste policy, the process of innovation and the techniques of technology assessment on opportunity for technology innovation. Limitations of the work are identified and future research development opportunities investigated.

Chapter Two – Literature Review

2.1 Introduction

To determine a suitable evaluation technique for opportunity for technology innovation in an IWMS, an understanding of an IWMS is needed. Economic, environmental and social drivers influence the performance of such systems and the opportunity for new technology. In the UK waste industry opportunity for new technology is affected by the interaction between the process technology and the human socio-economic factors influencing the evaluation of technology (EFIEA, 2003).

The chapter reviews the development of waste management models identifying their limitation to simulate the relationships created by interaction between these drivers.

The chapter identifies the inability of technology assessment techniques and waste management assessment models to evaluate the opportunity for technology innovation. Identifying their failure to consider the process of innovation (i.e. the different pathways for innovation and how the rate and timing of technology change can affect the opportunity for successful implementation of technology).

The thesis progresses in Chapters 3, 4 and 5 by describing the development of a waste management assessment model designed to evaluate the opportunity for technology innovation whilst addressing these limitations.

2.2 Integrated Waste Management Systems

Wilson (1998) in a review of European waste management practices identified a range of drivers that influence waste management and operational decision-making in an integrated waste management system:

(i) Policy, Management and Institutional Structure.
(ii) Operational Demands/Constraints.
(iii) Legislation.
(iv) Economic and Financial Factors.
(v) Social and Environmental Factors.

These drivers are described below with examples within the UK waste management systems:

(i) Policy, Management and Institutional Structure – An integrated waste management system needs to consider the long-term performance to achieve sustainable development objectives of EU environmental policy. In the UK local authorities and waste companies are reluctant to tie into such long-term contracts as there is too much uncertainty about the future, see (ix) below (Cozens, 2001).

(ii) Operational Demands/Constraints – As described in Chapter 1, section 1.2, the UK waste industry is currently dominated by the use of landfill as a disposal option with void space for landfill rapidly reducing. The industry is challenged to find alternative solutions for the disposal of waste. Chapter 3 will describe waste process technologies in detail identifying operational process demands/constraints that affect the performance of waste management systems and the opportunity for new technology.

(iii) Legislation – New technology is needed to adapt to the shifting demands of legislation. As described in Chapter 1, Table 1.1, this increase in legislation affecting Municipal Solid Waste has included:
  - The Packaging Directive 1994/62/EC,
  - The Integrated Pollution Prevention and Control Directive 1996/61/EC,
  - The Landfill Directive 1999/31/EC,
  - The Incineration Directive 2000/76/EC,
  - The WEEE Directive 2000/96/EC.
  - Animal by-products Act (EC) No 1774/2002.

(iv) Economic and Financial Factors – The availability of funding or subsidies can affect the opportunity for new technology and the performance of waste management systems. Whether a technology qualifies for subsidies or for additional taxes can make new technologies less or more attractive. Funding sources or subsidies such as the UK's Packaging Recycling Notes scheme can encourage the development of technology to recycle waste (DETR, 2000a).

(v) Social and Environmental Factors – Waste management systems are affected by the social and environmental impact of waste technologies and facilities. The public adoption of a Not In My Back Yard (NIMBY) attitude can cause planning costs to spiral as planning permission for waste facilities becomes an increasing problem. For example the Shank's Waste Group intended Mechanical Biological Treatment facility with incineration plant at Bletchley, Milton Keynes has been obstructed by numerous planning objections from the local community and environmental organisations. This has created additional costs as the planning application for the technology undergoes various public enquiries, rejections and appeals reducing the performance of the waste management system (Gascoigne, 2002).

The UK HM Treasury report 'The Green Book – Appraisal and Evaluation in Central Government', 2003, is designed to promote efficient policy development and resource allocation across the UK government. The report highlights other factors that need to be considered when evaluating the performance of policy and the opportunity for new technology in UK waste management strategies:

(vi) The perspective of the decision-maker.
(vii) The location and scale of the technology.
(viii) Technology performance in a wider integrated system.
(ix) The uncertain environment over time
(x) Risk Allocation.

(vi) The perspective of the decision-maker – Decisions relating to technology development need to be accountable to a range of Private, Public and Regulator stakeholders. Private waste companies will be seeking technology to provide a profit or return from their investment, the public will demand quality standards of service and the local authorities seek to achieve the require levels of regulatory performance. For example the decision by Milton Keynes council to change the collection of waste from weekly to fortnightly collection to reduce collection costs has had a negative effect on the public and the private operating waste company (Times Citizen, 2002). The decision was criticised by the public as waste built up outside their homes. The decision had a negative affect on the private waste company Shank's Waste Group such that eventually it withdrew its operation of the Materials Recovery Facility in Milton Keynes to which collected waste was sent. This was as the change in the collection process created additional costs in the running of the facility making it economically less attractive to them. The decision by the local authority to change the collection process would not have been the same if the decision had been made from either the public or private waste company perspective.

(vii) Location and scale of technology – The location and scale of technology can affect the performance and opportunity for new technology. The regulatory and operational structure for waste management in the UK creates artificial boundaries to technology in the UK waste industry (Lowe, 2002). Due to the fragmented structure of waste management in the UK (as described in Table 1.2) opportunities to realise benefits from varying the scale of facilities can be restricted. Waste authorities are often reluctant to share resources and collaborate when formulating strategy for waste management. This can be due to competition or rivalry between authorities with larger authorities often viewing neighbouring, smaller, authorities as potential burdens. The fragmentation of management can limit the size of facilities and the opportunity for economies of scale and economies of production to be realised.

(viii) Technology performance in a wider integrated system – It is important to consider the wider interactions of technology within an integrated management system. It is inadequate to assess technology in isolation as technology can influence other technology within a wider integrated system (Warner, 1962, Ettlie, 1986). For example in the waste industry the raw material 'waste' undergoes physical, chemical and biological transformations during an integrated waste management system. These transformations complicate the opportunity for new technology as the changing composition/characteristics of waste can affect the regulatory classification, handling properties and potential for pollution of the waste.

(ix) The uncertain environment over time – New technology needs to be able to sustain performance over time despite this uncertainty. In the waste industry uncertainty is associated with markets for recycled material, waste composition, transport costs, size of waste generation and regulatory standards etc. Table 2.1 shows the uncertainty and variation associated with paper material recycling prices over only a short time period of 3 years. In the UK, local authorities and waste companies resist becoming tied to contracts with technology that might become ineffective and obsolete during the contract life if markets for produced recycled material can not be guaranteed.

Table 2.1 - Paper market variation at 3 time points between 2001 to 2003.

Paper Type	**Market Price (£) (Source Letsrecycle.co.uk)**		
	05/03	05/02	05/01
Mixed	30	5-10	8-11
Newspaper & Pamphlets	45	25-30	22-27
Cardboard	55	40-45	30-40
White Office	40	50-52	53-55
Mixed Office	25	40-45	28-35

(x) Risk allocation – Given the risk associated with technology change, in the UK waste management contracts are becoming increasingly complicated to reflect the sharing of risk. To encourage technology development, performance related pay schemes and Private Finance Initiative contracts are emerging, as described in Chapter 1, section 1.2. In such schemes waste companies receive funding from the local authorities depending on their performance to attain recycling targets etc. This provides greater incentive to waste companies to improve technology efficiency above and beyond statutory targets.

2.3 Relationships between the drivers for technology in the UK Waste Industry

As identified earlier the opportunity for new technology is affected by the interaction between the process technology and the human socio-economic factors. Table 2.2 identifies examples of conflict and barriers to new technology in the UK waste industry created by such interaction. The relationships identified focus on the cost of policy and its impact on the opportunity for new technology from the perspective of a private waste company. As will be shown in section 2.4, a limitation of waste management models is their inability to simulate these complicated relationships and their impact on the performance of technology.

Table 2.2 – Examples of conflict between the Private Waste Companies objectives and the strategic objectives of policy in the UK waste industry (Lowe, 2002, Seaton, 2003).

Conflict of Interest	Private Waste Company Objectives	Strategic Policy Objectives
1 Long-term versus short-term planning	Private waste companies seek to secure long-term contracts to offset capital costs of technology made early on.	The continually shifting legislative 'goalposts' make it difficult to identify the long-term demands on technology.
2 The ability to sustain performance over time	To reduce the need for future investment waste companies seek to develop technology with the ability to sustain performance over time.	Local authorities are reluctant to support long-term technology initiatives with secured contracts or guaranteed markets for recycled or recovered materials due to uncertainty associated with the sector.
3 Capital cost – raising of finance for investment in technology	Private waste companies seek to recover or share the capital costs of technology to assist in generating the needed capital to meet the growing environmental legislation requirements.	Local authorities are reluctant to share the allocation of capital cost between the Private and Public stakeholders for fear of impact on political ambitions.
4 Risk Allocation	Private waste companies seek to reduce or minimise the risk as risk associated with unproven technology acts as a barrier to technology as higher returns on investment are sought from Banks and other money lenders.	The UK aims to develop the Private Finance Initiative scheme to share the risk between stakeholders through proposed profit relating schemes.
5 Spatial Boundaries	Private waste companies seek larger regional facilities where economies of scale and economies of production can be implemented offering potential cost savings.	Regulatory Authority Planning favours localised facilities supporting the 'proximity principle' in planning waste strategy. Some local authorities prefer to be independent.
6 Environmental Policy	Private waste companies argue that financial returns are compromised through the need to meet weak environmental legislation. Meaning technology might not offer sufficient financial reward to encourage investment.	Legislation objectives include: Single waste streams Recycling Targets BATNEEC, BAT, BPEO.

A review of technology assessment techniques and their inability to consider these relationships is identified in Appendix 2. As the thesis concentrates on the opportunity for technology innovation in the UK waste sector only the application of technology assessment techniques used in the sector are described below.

2.4 A Review of Waste Management Models

Barlishen, 1993, Macdonald, 1996, Dijkema, 2001, Abou Najm et al., 2002a and Morrissey and Browne, 2004 have all reviewed the use of waste management models in waste strategy planning. The ability to simulate the complicated waste management system is identified as the main limitation of waste management models. Morrissey and Browne (2004) classify recently development waste management models into three categories:
(i) Cost Benefit Models
(ii) Lifecycle Models
(iii) Multi Criteria Models

2.4.1 Cost Benefit Models

Cost benefit analysis is the assessment of all the costs and benefits of alternative options in monetary terms (ODPM, 2003). Non-monetary costs such as environmental or social costs are converted into monetary values. If the project benefits exceed loses then it has the opportunity for implementation.

Waste management models developed in the 1970's, 1980's and early 1990's were mainly 'Operational Research' optimisation models that focussed on single process, single waste stream or single evaluation assessment. The models were dominated by single economic assessment failing to account for the environmental and social impact of waste systems.

For example: Linear Programming – Abou Najm et al (2002).
The model is developed as a Municipal Solid Waste, decision support tool accounting for both socio-economic and environmental considerations. The model uses a linear programming optimisation formulation to evaluate the optimal waste strategy from collection, treatment to disposal. The model is designed to simulate an Integrated Waste Management System in Northern Lebanon identifying the least cost system design.

Other examples of cost benefit waste management modelling include Barlishen & Baetz (1996) who developed a mixed integer linear programming model to optimise the location, timing and sizing of waste management facilities in North America. Daskaloppoulos et al. (1998) developed a linear programming model to evaluate the economic and environmental impacts of an integrated municipal solid waste system from a single generation source.

Limitations of cost benefit modelling include the uncertainty in estimating monetary values of environmental and social impact. Often the complexity of the model designs can cause extensive re-parameterisation if the models are to support varying spatial assessment. Optimisation models are widely criticised as they only optimise suggested strategy and they do not identify opportunities for new technology (Morrissey and Browne, 2004). Models are often designed to optimise the waste management system not address the specific problems of waste managers. Optimal solutions are not always the most practical option in designing waste strategies, non-numeric issues such as availability of space can influence waste strategy. For example, at the Shanks MRF facility at Elstow, Bedford, insufficient storage space for recycled waste material if stored inappropriately can create breach operating permits and therefore it has to be disposed rather than recycled (Howard, 2001).

2.4.2 Lifecycle models

Lifecycle models have emerged as a justification technique for assessing technology in the 1990's. Life Cycle Costing involves identifying the costs over the lifetime of a technology, usually from research design to product disposal. Lifecycle models for the evaluation of the environmental performance of waste management systems have proliferated in recent years.

For example: UK Environment Agency WISARD tool (2000).
The model was developed by the Environment Agency in England & Wales and offered to local authorities as a software package to evaluate the environmental performance of waste management technologies and options. Lifecycle assessments of the individual components of an integrated waste management system such as waste collection, waste treatment technologies, landfill technologies and waste transportation technologies were created by various independent sources. These lifecycle reports were amalgamated creating the WISARD tool that provides a comprehensive evaluation of the environmental performance of waste management systems.

Other lifecycle analysis waste management models developed in recent years include the IWM-2, by MacDougall et al. (2001) and the EPIC/CSR, 2000, Integrated waste management model (IWMM).

Lifecycle analysis models have been widely criticised as they are restricted to assessing the environmental impacts only with no consideration for economic and social impact (Aumonier, 2000). They assess strategies at are single point in time rather than provide a dynamic assessment of performance. For example in a WISARD assessment of the waste strategy in the Bedfordshire region of the UK, the performance of different strategy options was identified at individual points in time i.e. 2010 and 2020 (BCC, 2002). Therefore what evidence is there that the same strategies are the most favourable strategies in the intervening years? Lifecycle analysis is not site specific and the results are inconclusive providing more subjective information. For example, in any assessment though the environmental impact of different strategy options is identified a decision as to whether potential aerial pollution is more important to consider than the potential for water pollution has to be made depending on the objectives of the decision-maker. LCA analysis does not address the other issues of system integration in terms of the change in characteristics of waste, the knock on effects of one process on another, the changes in waste handling properties and whether the strategy meets regulatory targets.

2.4.3 Multi Criteria Analysis Models

Multi-Criteria Analysis (MCA) models have been created to combine technology assessment to include economic, analytical and strategic assessment. MCA evaluates a range of technology options by establishing a set of objectives that can include financial and strategic performance objectives. These objectives are given measurable performance criteria to assess the extent to which they have been achieved by the technology. MCA techniques can be used to identify a single most preferred option, to rank options, to short-list a number of options or simply to distinguish acceptable from unacceptable (Office of Deputy Prime Minister, 2001).

There are different types of MCA techniques such as Linear Addictive models or Analytical Hierarchy Process models. Oeltjenbruns et al., (1994) creates an Analytical Hierarchy Process (AHP) MCA tool that allows simultaneous consideration of financial and non-financial objectives. It uses comparative judgements between pairs of criteria and options to identify a weighting system of influence for each evaluation criteria.

Waste management models using MCA techniques are emerging as the models become more integrated to consider a greater range of waste streams, technology options and impacts. For example, Powell (1996) evaluates six waste management disposal options, using a combination of cardinal valuation when numerical data was present and ordinal ranking schemes when numerical data was absent or unreliable.

MCA models are limited as there is uncertainty associated with the methodology and assessment technique as the allocation of weights is subjective (Morrissey and Browne, 2004). They also fail to assess technology of varying economic life.

2.5 Summary

Despite the developments in computer technology and waste industry knowledge, waste strategy models have not been widely adopted by waste managers (Aumonier, 2001, Lowe, 2002). The criticism of the individual models identifies generic problems with modelling in waste strategy planning:

- They fail to simulate the complicated waste management system or understand the relationships between the financial and socio-economic factors.
- They are 'weak' at allowing variation between spatial resolutions of assessment and fail to take into account localised conditions as it is often time consuming and costly to reparamaterise the models.
- They are 'weak' at addressing operational issues of waste process technologies such as the changing characteristics of waste, the knock on effects of one process on another or the changes in waste handling properties etc.
- They fail to simulate an evolving and dynamic system, evaluating systems and technology at single points in time.
- They fail to address the process of innovation i.e. understand the different types of innovation and the influence of the rate of implementation on opportunity for new technology. For example is it more favourable to develop a single 200ktpa Energy from Waste facility, given the environmental and social objections to such facilities? Or is it more favourable to develop the technology more incrementally

i.e. two 100ktpa Energy from Waste facilities to reduce the objections to the technology change process? What are the financial consequences of varying the rate of implementation of technology on the innovation process and how do they affect the opportunity for technology innovation?

The trade-off when developing models between simplicity to support model development against complexity to simulate the integrated waste management system affects the utility of the model. A model needs to be developed with the capacity to address the limitations of existing IWMS assessment models as identified in this chapter and be able to effectively simulate the complicated relationships within an integrated waste management system.

Chapter 3 describes waste process technologies in greater detail identifying the impact of operational demands/constraints on system performance and the design of the model.

Chapter Three – Processes within an Integrated Waste Management System

3.1 Introduction

This chapter identifies a range of operational issues that affect the opportunity for new technology in the waste sector by reviewing the design of an integrated waste management system. The chapter investigates the extent to which operational issues can be in conflict with other financial and human socio-economic factors that influence the opportunity for technology innovation. Through identifying these relationships these issues can be considered in the design of the waste management assessment model to address the limitations of waste management models, identified in Chapter 2.

3.2 The Definition and Composition of Municipal Solid Waste

There are different classifications of waste. This research addresses Municipal Solid Waste (MSW).

Municipal solid waste is household waste, street litter, waste sent to council recycling points, municipal park and garden waste, council office waste, and some commercial waste from shops and small trading estates where local authority waste collection agreements are in place (Defra, 2001).

MSW production varies in proportion to population and typically accounts for around 15% (by weight) of the controlled waste produced in an area (Environment Agency, 2001). An advantage of studying MSW is its similarity in characteristics to Commercial & Industrial (C&I) waste so technologies developed to process MSW can easily be transferred to process C&I waste streams (Environment Agency, 2001).

In 2000/1, 89% of MSW in the England was household waste (Defra, 2001). Household waste includes regular waste from household doorstep collections, bulky waste collection, hazardous household waste collection, communal collection of garden waste, plus waste from schools, street sweeping and litter. (Defra, 2000a, Office of Deputy Prime Minister, 2001) Household waste composition varies according to a number of social and economic factors. Table 3.1 shows an analysis of the average composition of household waste.

Table 3.1 – Average Composition of Household Waste 2000/1, (Parfitt, 2002)

Waste Materials	Percentage of Waste %
Garden Waste	20
Paper and Board	18
Kitchen Waste	17
General household scrapings	9
Glass	7
Wood	5
Scrap metal/white goods	5
Dense plastic	4
Plastic Film	4
Textile	3
Metal packaging	3
Nappies	2
Soil	3

In the waste industry, a source of uncertainty impacting the performance of waste management systems and the opportunity for new technology is waste composition. Tukker et al. (2003) forecasts how household waste composition will vary by 2020. They identify 4 trends or developments affecting waste composition as society and attitudes evolve over the next 20 years. These scenarios, described below, are intended as theoretical extremes of society evolution to represent potential extremes in the variation of waste composition. These scenarios identify how environment uncertainty could affect waste composition and technology performance over time. Tukker et al. (2003) argues that waste composition will vary according to:

i. The place where functions are fulfilled and thus the location of where waste is generated e.g. the shifting of workplace from offices to home.
ii. The extent of materialisation or dematerialisation e.g. technology (electronic devices) replacing traditional materials (paper).
iii. Individual behaviour e.g. the extent of support for source separation schemes.

He identified four scenarios of potential future society:

a) 'Media@home' (M@H) – a consuming culture with electronics dominating the household, with work, schooling, socialising and shopping all conducted on the electronic highway from home.
b) 'On the Road' (OTR) – people want flexibility as social interaction and fun are highly valued. Multifunctional, light and portable products are created to support a society that is continually on the move. With society becoming increasingly fashion conscious a disposable society is created with products developed with short-lifespans.
c) 'Comfort community' (CC) - emphasis is on social values instead of possession of products, more of a communal community where services/products are provided and shared within a community.
d) 'Home sweet home' (HSH) - emphasis on living in the moment, people appreciate good quality products that last and are reliable with a demateralised society.

Using a mathematical formulae and calculation method the paper identifies the waste composition for these future societies. Future household waste generation is calculated as a direct function of Organisation for Economic Development (OECD) forecasts of private expenditure data. (This calculation process is described in greater detail in the appendix.)

$$F = \sum_I X_I * \alpha_I * \beta_I * \gamma_I$$

Where

F	Amount of waste generated by function f (e.g. kitchen waste)
X_I	Baseline amount of the waste type which is characteristic for a function (e.g. the amount of kitchen waste in 2020 calculated as the product of kitchen waste in 1995 multiplied by expenditure growth on food)
α_I	Indoor factor (scenario-specific)
β_I	Materialisation factor
γ_I	Management factor

The results are summarised in Table 3.2 below.

Table 3.2 - The table shows the amount of waste generated by function as a value (Scenario Calculations Total waste generation in 1995 = 100 units, Total waste in 2020 =143 units) (Tucker et al. 2003)

Waste Type	1995	2020	M@H	OTR	CC	HSH
Composting waste	29	40	57	24	18	35
Packaging	16	19	33	12	12	19
Paper	12	18	80	24	6	27
White and Brown goods	2	3	8	8	2	3
Other	41	63	144	46	35	75
Total	100	143	322	113	73	160

M@H – shows an increase in all waste as the home is the focus of operation, with a significant increase in paper waste.
OTR – only a minor reduction in MSW as people are continually on the move with light portable products created. No significant changes in waste composition though Paper increases by 100% and Composting decreases by 16%. Quantities are relatively small compared to other scenarios i.e. OTR total of 113, M@H total 322.
CC - shows a reduction in the generation of waste across all waste materials, this is contrary to all predicted waste forecasts that view waste generation as growing.
HSH – Paper and other waste materials increase but others stay approximately the same.

This variation in waste composition over time is important to measuring the performance of technology over time. The uncertainty of waste composition over time highlights the difficulty in developing a long-term strategy in waste management systems. It is difficult to justify long-term contracts and planning if the resource of the system (waste) is continually changing over time. Through greater understanding of technology performance over time, technology that is better suited to sustain performance in such an uncertain environment could be identified. In the design of the model it is important to have the capacity to reflect this variation in waste composition thus addressing a limitation of existing models. This variation in waste composition will be used in Chapter 8 when modelling exploration of technology options over time to reflect uncertainty.

3.3 The Transformation of Waste

Technology performance and the opportunity for new technology in the waste industry is further complicated as the waste material (i.e. MSW) changes physical, chemical and biological characteristics as it is transferred within the system. The transformation physically, chemically and biologically can effect the regulatory classification, handling properties and potential for pollution of the waste.

- Physical transformation. Waste can be transformed physically in size, shape, and volume by various collection, treatment and disposal processes within the system e.g. if recycling glass bottles in their original state they can be safely handled, through bulking the broken glass it becomes a handling hazard.

- Chemical transformation. Treatment processes can cause chemical transformation from a stable, non-polluting material to an unstable polluting material e.g. when waste undergoes treatment through incineration the physical characteristics are altered as a gas is produced from a solid. The waste in its solid state was potentially not polluting (i.e. paper), through incineration the waste is transformed into a gas creating a new pollution potential through the emission of carbon dioxide etc.

- Biological transformation. Some components of MSW are biodegradable such as kitchen or garden waste etc. Depending on the environmental conditions the waste has a potential to degrade changing physical and chemical characteristics. E.g. If waste is disposed to landfill, the biodegradable components degrade and transform producing potentially polluting leachate and landfill gas.

This transformation of waste further complicates the design of integrated waste management systems. The fragmented structure for waste management in the UK is impacted by this transformation of waste. For example, in Milton Keynes, though Shanks Waste Group managed and operated the Materials Recycling Facility the waste collection process was managed by Cleanaway Ltd. With being unable to control the source separation and composition of collected waste the cost performance of the MRF diminished resulting in the Shanks Waste Group opting out of its contract to manage the MRF (King, 2003).

3.4 Waste Technologies

An integrated waste management system incorporates waste management from generation to disposal. There are various opportunities for different collection, treatment and disposal technologies. Within this research they include:

Waste Collection Schemes

- Household
  - Bulk collection
  - Blue box
  - Orange bag
- Bring sites e.g. bottle banks at supermarkets
- Household waste recycling centres (HWRC's) and civic amenity sites

Waste Treatment Technology

- Material recovery facilities
- Composting plants
- Energy from waste
- Mechanical and biological treatment technologies e.g. ecodeco

Disposal Technology

- Landfill

Below are descriptions of these processes within an integrated waste management system. The technologies are widely known and greater detail descriptions can be found in most waste management textbooks and in key journals e.g. Tchobanoglous et al. (1993), the ENDS Report, Wastes Management etc. It is not necessary to understand the intricate technical components of a process but to understand the operational constraints of each process. The aim of the descriptions is to identify the key characteristics of each technology that affect the opportunity for its implementation in the system. Through understanding these characteristics the conflicts with the human socio-economic factors influencing opportunity for new technology can be better understood.

3.4.1 Waste Collection Schemes

In the UK waste collection authorities (WCA's) delineated by District councils are responsible for the collection of waste. The duties are largely contracted out to private waste companies with various schemes employed for waste collection. Below are brief descriptions of the types of waste collection systems operational in the UK (Sampson, 2000, Environment Agency, 2003, IWM, 2000)

3.4.1.1 Household Bulk Collection

Unsorted MSW is traditionally collected using wheelie bins in the UK. Within this thesis bulk collection refers to the disposal of waste which is unsorted. Bulk collected waste can, and usually is, combined with other kerbside collection schemes that involve the sorting of recyclable materials prior to disposal. This is known as co-collection.

3.4.1.2 Kerbside sort recycling schemes

These types of scheme require the householders to place recyclable materials in a separate container. Typical types of containers used include the Survival Bag (orange bag) scheme or the Blue Box scheme. The types of material that should be sorted and placed in the different containers can vary from scheme to scheme. In the UK, paper, glass, plastics, and metals are the most widely separated materials. Collection vehicles can have different compartments for storing these sorted materials or separate waste collection vehicles can collected the waste.

Process Advantages

- It is a way of involving the public in the participation of protecting the environment through recycling.
- It aids the next stage of waste processing at the Material Recovery Facility potentially reducing further costs within the system.
- Kerbside sort schemes help attain recycling targets set by the increasing legislative environment.

Process Disadvantages

- They rely on the support of the public, which is costly to maintain through advertising and promotion schemes.
- Collection costs might increase as it is more labour intensive and collection time increases.
- Contamination of the separated waste is a problem, though this is the case for all types of waste collection. Contamination is through mixing sorted waste materials with unwanted materials. The kerbside schemes are reliant on households correctly separating material otherwise the material might be rejected further along the waste management system. As will be discussed in Chapter 4, when allocating the cost of waste management systems and new technologies the public are reluctant to accept additional financial cost of such services arguing that they are already burdened by the need to comply to such source separation schemes. Therefore why should they pay the additional cost for improved services when they have an increasing responsibility in the system?

3.4.1.3 Bring Sites

Bring sites is the name given to municipal waste collection banks such as bottle banks, paper banks or clothes banks. These facilities are often located at sites that the public visit on regular occasions enabling them to dispose of their waste whilst completing everyday activities such as shopping. This reduces the environmental impact of extra transport journeys for waste disposal. Contamination is again a problem at Bring sites with the system reliant on the public to correctly sort waste into the material categories.

3.4.1.4 Household Waste Recycling Centres (HWRC's) and Civic Amenity Sites

These are larger waste collection facilities that allow the disposal for bulky goods and garden waste. The types of waste collected include garden waste, metals, paper, plastic and glass.

3.4.2 Material Recovery Facilities (MRFs)

A MRF is a plant which separates, processes and stores recyclable material before being sent on to a 'market' e.g. a material reprocessor or an additional treatment technology or if unsuitable for market sent for disposal to landfill (Environment Agency, 2003, IWM, 2000). MRFs can be either clean MRFs where recyclable materials are recovered from source separated material or dirty MRFs where recyclable material is recovered from unsorted dustbin waste. MRFs can be designed to sort and separate different waste materials e.g. paper, plastic, glass, ferrous (e.g. iron and steel) and non-ferrous (e.g. aluminium) metals. Each waste material can then be diversified further into individual categories e.g. paper to office, white paper, cardboard, mixed paper etc. The technology in the MRFs varies according to the waste materials that are to be recovered. Sorting can be through manual labour with a line of pickers recovering materials from a conveyor belt or it can involve more mechanical equipment. High efficiency MRFs can process up to 7-8 separate recyclable material streams from the dry mixed feedstock. Equipment used in MRFs to separate waste streams include:

- Disc screens can separate paper and card into different grades.
- Optical sensors can separate plastics by polymer type e.g. Plastic sorting at the Milton Keynes MRF sorts mixed plastic into clear PET, coloured PET, natural HDPE and Coloured HDPE through light beams with manual sorting employed to identify PVC.
- Metals can be separated into ferrous and non-ferrous fractions via overband magnets and eddy-current separation respectively.

The choice of materials to recover does not necessarily depend on the economic cost of recovery versus potential revenue. Other factors that influence the decision include the amount of storage space, time constraints, transport costs, market stability, regulatory targets or socio-political reasons, as will be discussed in Chapter 5.

There are minimal environmental impacts associated with MRFs frequently the main issues the generation of biologically active dusts, which can be a potential hazard to workers and neighbours. Handling of materials can create health and safety issues as materials are processed through the facilities and can be transformed e.g. glass bottles which were easy to handle become dangerous broken glass. Traffic noise for deliveries and export can be a source of environmental pollution.

Process Advantages

- MRFs recover higher volumes and better quality material for recycling markets at increased prices.
- Costs can be reduced through adopting economies of scale when building new facilities.
- Low technology MRFs that are dominated by hand sorting add flexibility to the selection of materials to recover.

Process Disadvantages

- Segregating dry recyclable material is likely to increase costs for collection.
- Though MRFs can operate with different waste collection schemes, efficiency is improved when the waste collection scheme and the MRF are integrated together e.g. in Milton Keynes the waste collection service is operated by Cleanaway and

the MRF operated by Shanks. Measures to reduce costs through varying the collection process by Cleanaway have made the efficiency of the MRF uneconomic for Shanks (King, 2003).
- MRFs are unlikely to deliver recycling targets in isolation.
- They can be inflexible to market uncertainty if adopting advanced technology e.g. to recover the capital costs of plastic sorting technology long-term contracts are needed.

3.4.3 Composting

Composting is the aerobic decomposition of biodegradable material producing a residue called compost. Composting can take between 12 to 20 weeks until the active phase of composting is complete. The biodegradable fraction of MSW can be treated by composting this is primarily kitchen and garden waste but can include paper and fines material. Different types of composting facility have been engineered to create compost as a treatment technology for organic waste. Home composting requires householders to separate and compost their own kitchen and garden waste using home composting units. Centralised composting is where larger scale composting plants serve an area. The main product from composting is compost as a soil conditioner though the markets in the UK are only emerging and rather unstable at present.

The environmental impacts associated with composting include emissions to air of bio-aerosols, volatile organic compounds, odours and dust. Leachate from composting can be a potential hazard to surface or groundwater if it is released without treatment. Cross contamination with animal by-products e.g. foot and mouth is a growing concern.

Process Advantages
- Composting stabilises waste limiting the potential for leachate pollution.
- It reduces waste volume and it reduces the amount of waste sent to landfill.
- It has economic value as can be used as a product.

Process Disadvantages
- The forthcoming EU Animal By-products Regulation (as identified in Table 1.1) is potentially steering the industry to higher regulatory standards. This should help improve the quality and marketability of the compost produced but at ‘extra’ cost (Chapter 8 investigates this ‘extra’ cost).
- The UK market for compost material is uncertain, if composting becomes as widespread as anticipated the market might quickly be saturated.
- Contamination in composting is a critical issue as the quality of compost affects its potential market value. The main contamination of compost is of plastic film with the only effective removal method through labour intensive hand picking.
- There are concerns over home composting being unregulated with the potential that garden waste could be mixed with garden chemicals creating environmental pollution.

3.4.4 Mechanical Biological Treatment (MBT) – e.g. Ecodeco, Herhof, Bedminster technologies

Mechanical Biological Treatment (MBT) is a generic name for a range of processes where MBT bio-stabilises the mass of residual waste, the recyclable material is recovered, the organic fraction is composted and energy is recovered via Refuse Derived Fuel (RDF) production. Different MBT technologies include Ecodeco, Herhof, and Bedminster. These MBT processes are technologies operational in other parts of the EU but only emerging in the UK. The research uses the MBT Ecodeco technology as an example of the range of MBT processes.

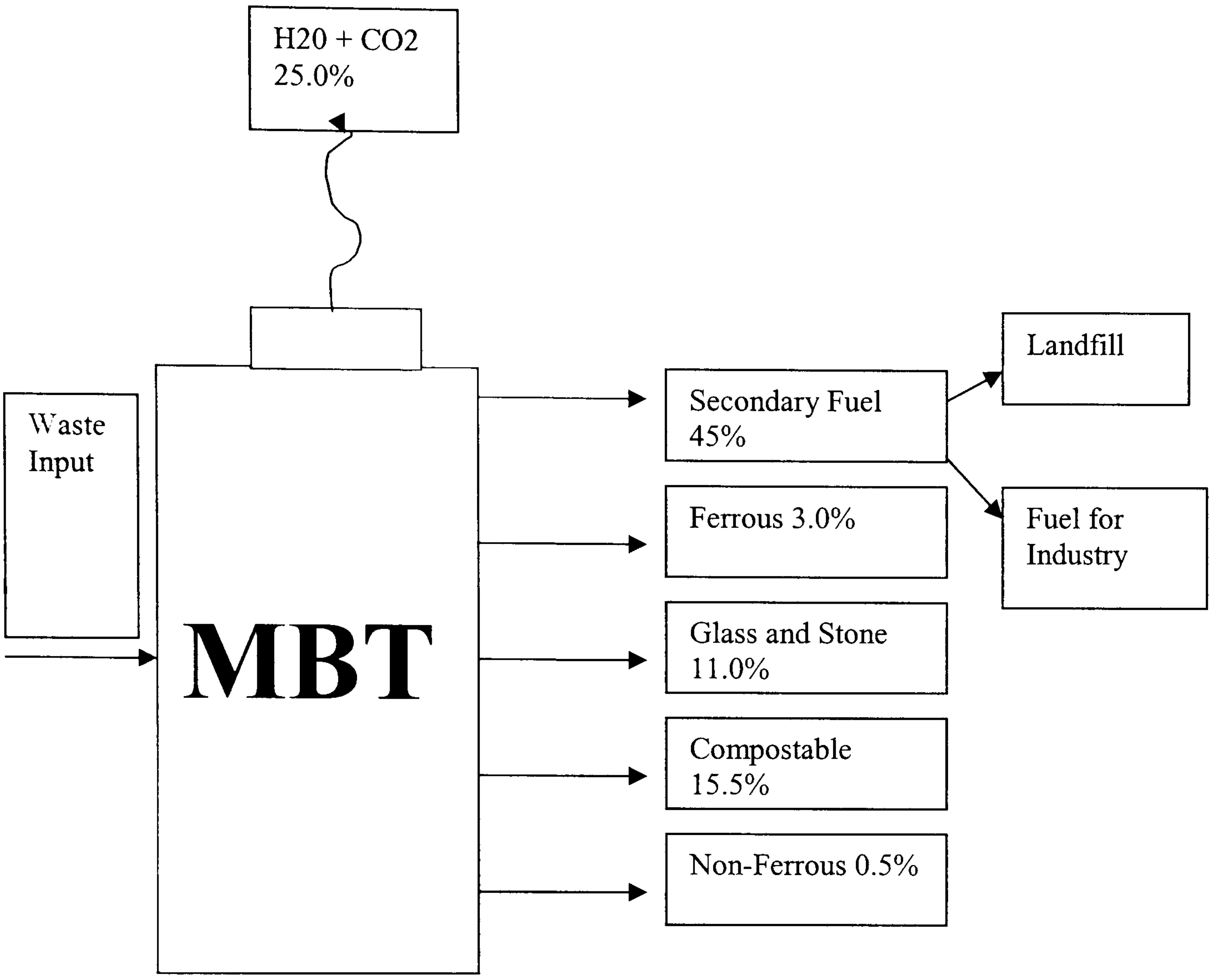
3.4.4.1 Ecodeco - Introduction

Ecodeco is a MBT technology originating from Italy and developed by Sistema Ecodeco SpA (Greater London Authority, 2003). The process utilises the energy produced through the biodegradation of MSW to produce a stabilised waste material suitable for use as a refuse derived fuel. Sistema Ecodeco currently operates process plants in Italy with Shanks Group introducing the Ecodeco process to the UK.

3.4.4.2 Process Description

Waste is unloaded into a reception pit with an elevated perforated floor. Air is circulated through the waste to prevent stagnation and remove unwanted odour whilst the waste is shredded to a size of 20-30cm. This increases the surface area to make the waste more accessible to oxygen for the degradation process. The shredded material is transported to the aerobic fermentation area and placed in a series of windrows in a grid pattern on a perforated floor. The circulating air bio-dries the waste. The produced material is stabilised, sanitised and virtually odourless with the air discharged to the atmosphere via biological filters. The air-flow is controlled by computer to maintain a stable temperature with an average process time to stabilisation of 12-15 days. The stabilised material is transported to the recycling and recovery area. Here the material is separated using a combination of sieving, weight separation and metal extraction. The products include ferrous, non-ferrous metals, glass & stone and compost material. Figure 3.1 shows the mix of these constituents after treatment via the Ecodeco process. The stabilised fraction (approximately 45%) can be landfilled or converted into Refuse Derived Fuel (RDF) pellets. RDF describes waste that has been processed to improve the fuel characteristics. The aim of producing RDF is to maximise the energy recovery from waste whilst minimising cost and size of the combustion and heat recovery plant. RDF can be split into coarse, floc or densified RDF.

Figure 3.1 - Typical separation of MSW by the Ecodeco MBT technology (Sistema Ecodeco, 2000).



Environmental emissions from the Ecodeco process are controlled. The bio-filter emissions to air have a minimal impact on local air quality. Effluent produced by the technology is captured in storage tanks before transfer to sewage treatment works. The solid residue consisting of fine, inert material is disposed to landfill. Construction and planning periods can vary from 39-60 months depending on the planning application. Facilities are built in multiples of 60,000 tpa modules.

Process Advantages

- It offers a treatment technology for unsorted bulk waste.
- Ecodeco offers a second bite at the 'recycling cherry' by recovering recyclable fractions from the residual waste after source separation schemes.
- Ecodeco offers the opportunity to meet growing legislative demands for increased recycling targets, diversion of biodegradable waste from landfill or an increase in recovery of value from waste.
- The process is a self-contained treatment technology with minimal impact on the local environment.
- The process develops Refuse Derived Fuel pellets as a fuel for energy recovery.
- The biomass content of the RDF would qualify for renewable energy obligation subsidy.

Process Disadvantages

- RDF producing technology is often viewed by the public as incineration by another name.

- There is uncertainty associated with the market for RDF.
- Quality of compost material produced is variable with health implications involved in using MBT products as bio-fertilisers.
- There is a lack of suitable combustion sites for RDF in the UK e.g. only at Baldovie Incinerator in Dundee.

3.4.5 Incineration – Energy from Waste

Energy from waste (EfW) is the combustion of waste under controlled conditions where the heat is recovered for a beneficial purpose. There are different types of incineration systems, Mass burn with fixed gate, rotary kiln grate, fluidised bed, gasification and pyrolysis. The heat produced maybe used to provide steam or hot water or electricity. Combined heat and power (CHP) incinerators provide both heat and power. Municipal solid waste has a calorific value approximately one third that of coal (ETSU, 2000). EfW is regarded as a treatment technology not a disposal option for waste as ash residues need disposal after incineration.

Public environmental concerns associated with EfW have been centred on the emissions to air from plants. Increasing environmental legislation, as described in Chapter 1, including the 1989, 1996 and the pending Incineration Directives have all helped improve incineration performance since the 1990's. Increasing regulatory standards and improving gas-cleaning systems restrict the emissions to atmosphere. These systems in the past have been economically costly to install making incineration economically less viable than landfill. As gas clean up technologies have improved in recent years the costs have reduced making EfW more competitive to landfill. This thesis evaluates the opportunity for technology innovation through the advanced thermal treatment technology Pyrolysis. This technology is operational in other parts of the world but yet to establish itself in the UK.

3.4.5.1 Differences between Mass Burn EfW and Advanced Thermal Treatment technologies such as Gasification & Pyrolysis (Porteous, 2001)

Gasification is the partial combustion of the carbonaceous components of the feedstock usually in the temperature ranges of 900-1600°C . Pyrolysis is the thermal decomposition in the absence of oxygen usually in the temperature ranges 400-800°C. These advanced processes support:

1. Improved dioxin destruction.
2. Are operational under varying CV feedstock ranges.
3. Adopt improved flue gas cleaning of heavy metals and dioxins.
4. Adopt ultra high performance gas scrubbers and bag filters.

3.4.5.2 Advanced Thermal Treatment Technologies - Pyrolysis

Pyrolysis is an endothermic process in the complete absence of an oxidising agent in which carbon-based matter is chemically decomposed. Pyrolysis occurs at temperatures between 400-800 °C. Pyrolysis produces gas, liquid and solid char.

3.4.5.3 Process Description

The plant pre-sorts MSW to remove low calorific material and bulky goods. The residue is shredded to a maximum particle size of 200 mm. Low temperature pyrolysis (around 450 °C) occurs in a rotary drum. Waste is resident in the drum for approximately 1 hour, condensable liquids are present in the 'pyrolysis vapour' which is transported through pipework to the combustor. Hot solids are separated from the syngas and passed through a handling system where, after cooling, metals are removed. The remaining solid residue comprising of combustible char and inert material is crushed to a size of 1 mm before being transferred to the high temperature combustion chamber. Here the crushed material is mixed with the syngas and combusted at high temperature (around 1300°C). The high temperature due to the syngas leads to more efficient combustion than mass-burn incineration. It is designed to minimise the potential for dioxin formation, reduce nitrogen oxides production and convert ash into a vitrified 'glass like' inert ash. The flue gases exiting the furnace are transferred to high temperature air-heaters where they indirectly heat the pyrolysis drum. A support fuel is needed for start-up and shutdown and emergency situations. The waste heat boiler receives heat from the high-temperature air-heater with the boiler generating steam for an electricity turbo-generator. Flue-gases are cleaned via two bag filters the first collects fly ash and boiler ash particles. These are recycled to the high combustion chamber to remove the need for landfill disposal. The second bag filter is fitted with a lime injection system to provide acid gas emission abatement. The collected material, a combination of unreacted lime, calcium sulphate/sulphide and calcium chloride, is managed in a hazardous waste landfill site.

Emissions to air are compliant with EU Waste Incineration Directives and acid gas residues from filters are sent to landfill. Water separating from the produced liquid fuel requires treatment. Design to commissioning can take between 12-30+ months for 120 ktpa facilities.

Process Advantages

- EfW processing of waste reduces overall waste volume and reduces disposal to landfill.
- Advanced thermal treatment through Pyrolysis offers improvement in the quality of flue gases and the solid residues from the process compared to mass burn incineration.
- Pyrolysis is very efficient at the destruction of dioxins and other organic species.
- Pyrolysis can produce a stable granulate instead of ash which can be used as an aggregate for building.
- Pyrolysis plants are typically smaller in size to mass burn incineration.

Process Disadvantages

- Pyrolysis as a waste treatment technology is not yet proven in the UK, though commercial plants are operating in Japan.
- The process requires source separation and recycling schemes to enhance the calorific value of the input waste and the efficiency of the process.
- Due to the high capital costs in building EfW plants long contract periods for dealing with waste are needed to payback the investment, this can reduce contract flexibility.
- EfW in the UK has a poor media image though this varies through the EU.
- Banks regard EfW technologies with extreme caution due to their poor media image.
- EFW is exempt from Renewable Obligation and benefits.

- There is difficulty in securing long term heating contracts for the recovered energy from waste.
- Incineration does not contribute to recycling targets as it is a recovery process.

3.4.6 Landfill

Landfill is the controlled deposition of waste to land it provides containment and stabilisation of MSW over time. Landfill is a favoured waste strategy in the UK due to suitable geological and economic conditions. It is perceived as a low risk technology in terms of financing. The environmental concerns associated with landfill technology relate to landfill gas and leachate. Landfill gas consists of 50-60% methane and 35-40% carbon dioxide. Landfill gas can contribute to global warming, alternatively it can be recovered through gas collection systems and used for electricity generation. Landfill can also create unwanted odours. With the increasing legislation relating to landfill the disposal of waste to landfill needs to be reduce in coming years. The landfill void space in the UK is rapidly reducing and the increasing landfill tax is making landfill less favourable.

3.5 Summary

This chapter has reviewed waste industry technologies. The chapter has introduced operational demands/constraints applicable to technology in the waste industry. For example technology performance is affected by:

- Waste Composition – 'waste' changes composition over time in response to the changing social and economic conditions.
- Waste transformation – the raw material 'waste' changes characteristics as it is processed by the technology within a waste strategy.

The chapter has identified operational demands/constraints of individual technologies:

- Waste collection – the reliance on the public to assist in source separation and collection schemes,
- Materials Recovery Facilities – the health and safety of workers,
- Composting – the cost and impact of biodegradable waste legislation,
- Mechanical Biological Treatment – the uncertainty over markets for Refuse derived fuel,
- Energy from Waste – the high capital cost of technology,
- Landfill – the reducing void space in the UK.

In designing the model to evaluate waste technology options the operational demands/constraints on technology need to be considered as they can affect the performance/efficiency of technology. Chapter 4 will describe the development of the model identifying how these operational demands/constraints were considered in the model design to address a limitation of existing waste management models (as identified in Chapter 2).

Chapter Four – Approaches to modelling an Integrated Waste Management System

4.1 Introduction

As identified in Chapter 1, an integrated waste management model is developed to assess the opportunity for new technology through identifying the cost of compliance to waste policy.

The model will be used to investigate the cost of different waste strategy options and be used to evaluate the impact of policy on opportunity for technology innovation. As identified in Chapter 2 previously designed waste strategy assessment tools have been widely criticised for their failure to simulate the complicated relationships within an integrated waste management system. This chapter will highlight the numerous design issues that need to be considered when designing the model. For example, should the model adopt a multiple waste stream approach or be able to assess different spatial scales? This chapter describes how these key design issues were considered in the model development highlighting how failure to consider them in the model might impact the results and the opportunity for technology innovation.

The model must provide a mechanism to evaluate different waste strategy options and be able to incorporate the range of decision drivers identified in Chapter 1 that influence the decision process when evaluating opportunity for technology innovation. In Chapter 1 it was argued that the opportunity for technology innovation will be measured by the cost of implementing that technology into the system, therefore the model needs to be able to calculate the cost of variation to waste strategy through the development of new technologies.

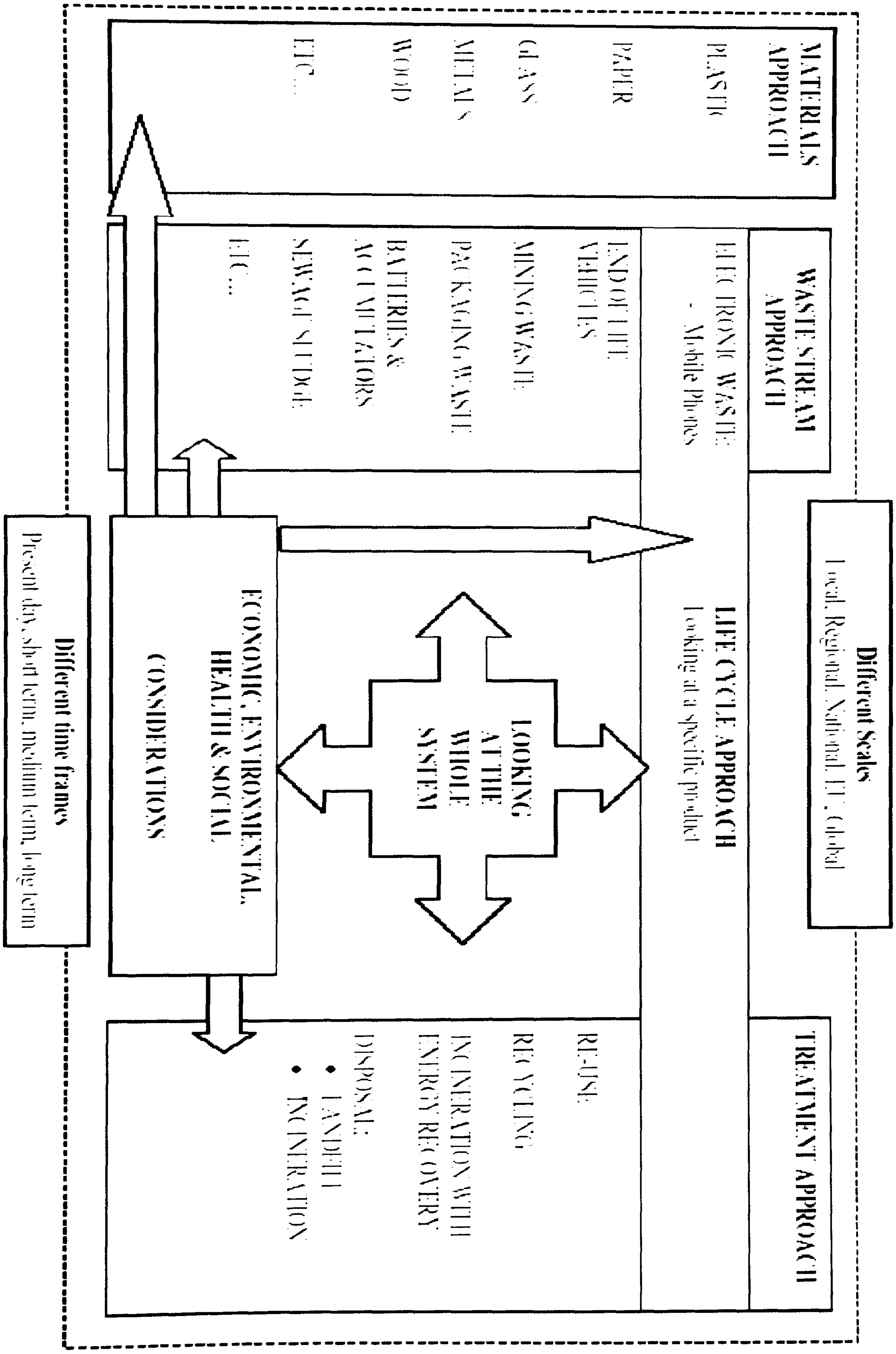
Figure 4.1 identifies potential approaches to integrated waste management assessment identified by the Institute for European Environmental Policy (EFIEA, 2003). Three potential approaches are identified:

- A materials approach e.g. plastic waste
- A waste stream approach e.g. packaging waste
- A treatment approach e.g. recycling technology.

These approaches have emerged in part in response to the development of EU Environmental Policy as described in Chapter 1 and in part due to the development of modelling techniques described in Chapter 2.

This chapter will discuss how failure to consider variation to these and other model design issues can impact the opportunity for technology innovation. Through understanding the impact of these issues further understanding of the design and implementation of EU waste policy can be gained. This is as these approaches have evolved in response to policy.

Figure 4.1 – Potential Approaches to Integrated Waste Management System Assessment (EFIEA, 2003)



4.2 Model Design and Development

4.2.1 Different spatial scales of assessment - multiple region modelling versus single region modelling

Chapter 2 reviewed waste management models are criticised for their failure to simulate the impact of varying spatial decision level on technology performance. 'Artificial' spatial barriers to new technology are created by the fragmented management structure, political boundaries and environmental policy in the UK waste industry. The model needs to be designed to support exploration of technology options on a varying spatial scale to assist in overcoming these barriers. This would allow investigation into the aggregation of scale/capacity of technology to reduce technology costs through economies of scale and economies of production. A two tiered spatial resolution approach to modelling is adopted:

(i) Bedfordshire sub-region.
(ii) East Anglia region.

The model is designed to replicate the waste management system in the Bedfordshire sub-region of the UK, this being the current spatial decision level for waste strategy planning. In this thesis Bedfordshire sub-region means a collaboration of Bedfordshire County Council, Bedford Borough Council, Mid Beds District Council and Luton Borough Council. These authorities form the Bedfordshire sub-region as they have joined together to develop a strategic vision for managing waste in the region for the future. Another advantage is that they developed their strategy based upon the Environment Agency's Life Cycle Analysis 'WISARD' tool (BCC, 2002) that evaluates waste strategy based upon the environmental performance of technology. This has benefits in that it allows comparison of modeling results and data sources for modelling in the Bedfordshire sub-region have already been identified by the WISARD analysis.

Bedfordshire is located in the East of England region (See Figures 4.2 & 4.3). The East Anglia region is selected as the second spatial decision level to model given its role as a Regional Technical Advisory Board (RTAB) planning region and the UK policy shift towards regional strategy. Through modelling these different spatial levels the impact (cost) on system performance due to the policy shift from local waste management to regional management can be investigated.

The East of England region is made up of six shire counties Cambridgeshire, Norfolk, Suffolk, Essex, Bedfordshire and Hertfordshire and four unitary authorities, Peterborough, Southend-on-sea, Thurrock and Luton. The population for the region was nearly 5.3m in 1996 and is expected to rise to around 5.9m by 2021 (Environment Agency, 2001). Sedimentary strata including Oxford and London Clay has created a favourable geologically environment for the development of landfill waste disposal facilities in the region. This supported 119 active landfill sites in the region in 1999.

Figure 4.2 - Waste Strategy Planning Regions in England and Wales (Environment Agency, 2001)

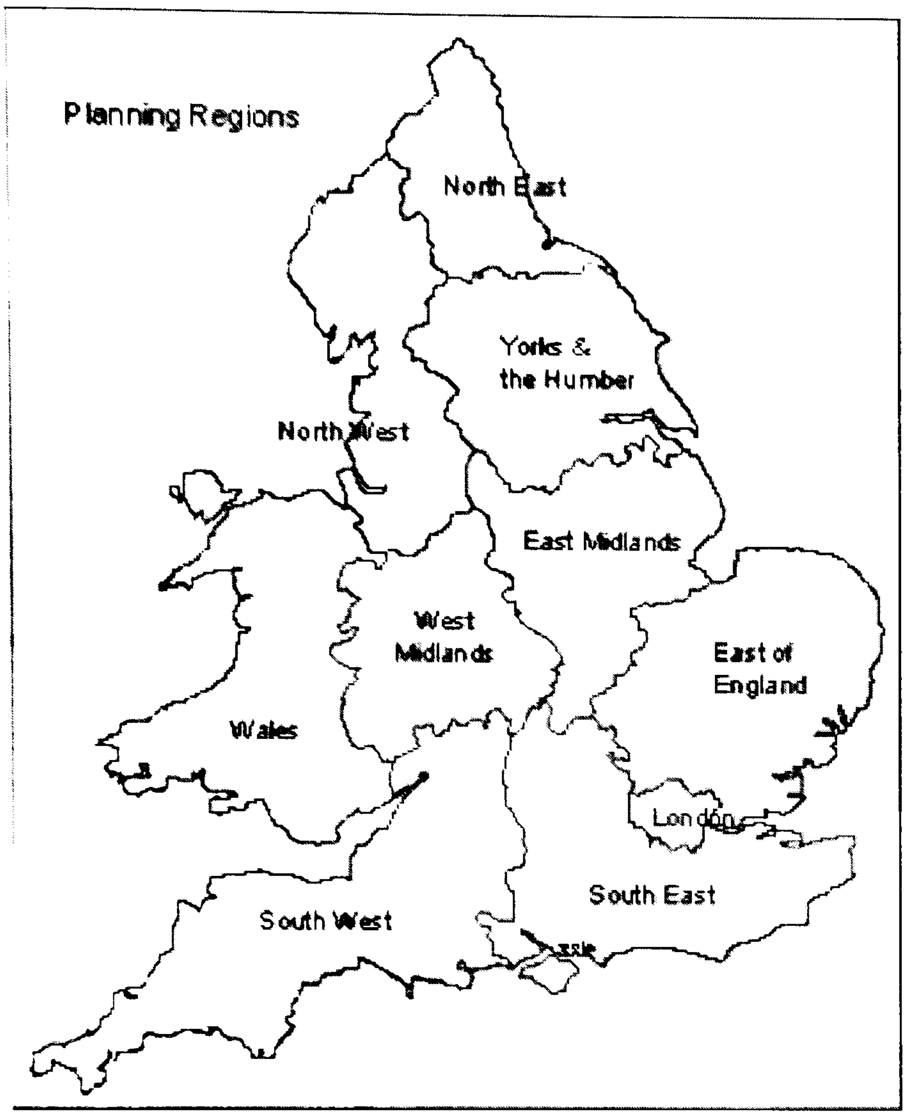
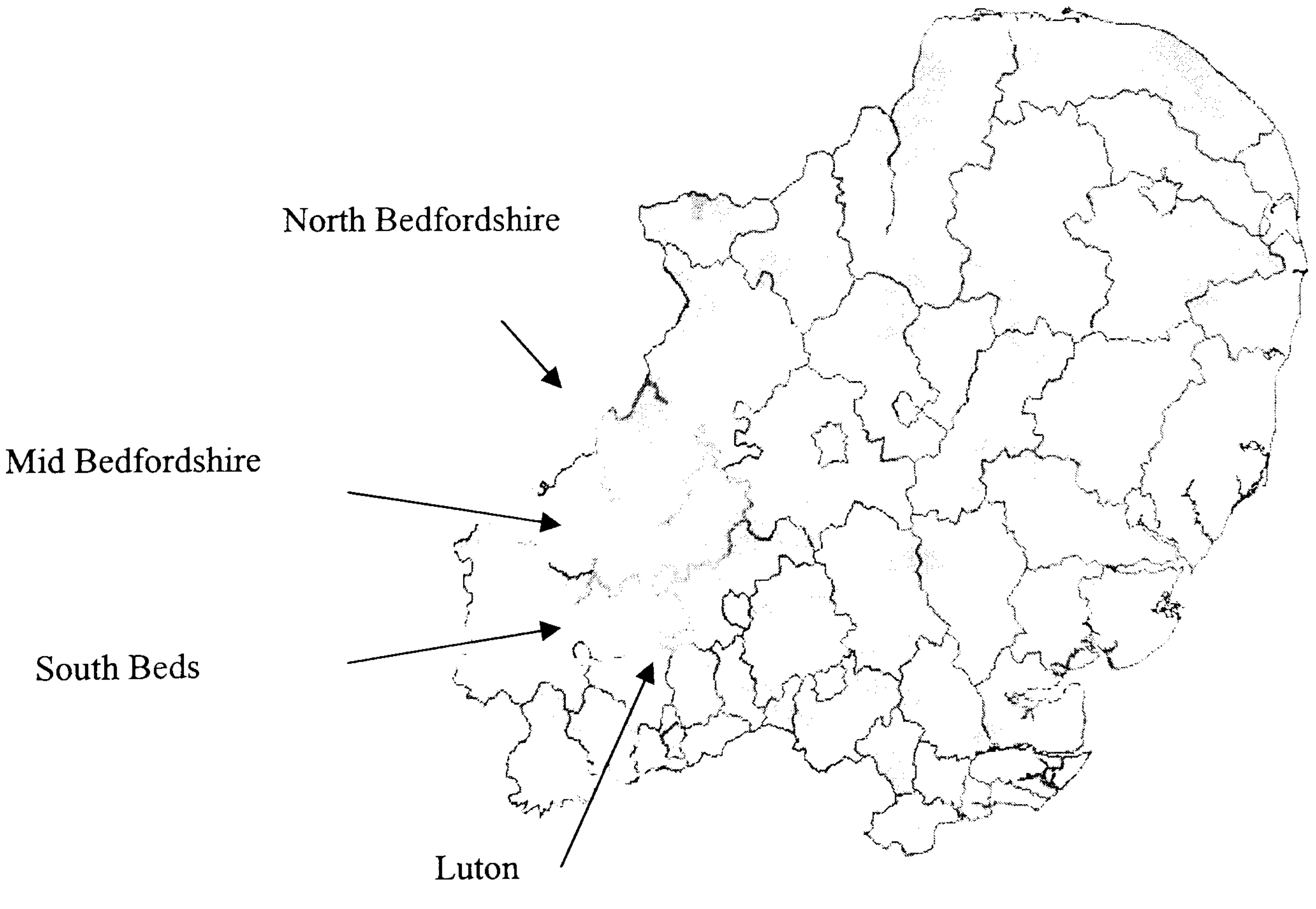


Figure 4.3 - Location of Bedfordshire sub-region in East Anglia (Environment Agency, 2001)



In 1999, 226,980 households generated 4,186 tonnes of MSW per week in Bedfordshire, of which 66% was collected using the dry recyclable source separation 'Orange Bag' scheme, 23% using a 'Blue Box' source separation scheme, with the remaining 11% collected in bulk (BCC, 2002). A further 1,219 tonnes per week of MSW was collected via Civic Amenity sites and 168 tonnes per week from Bring Sites e.g. bottle banks at supermarkets. The waste is transferred to two Materials Recovery Facilities where Paper, Plastics, and Metals are separated for recycling and transported to market (See Table 4.2). There is a single composting plant in Bedfordshire receiving around 72 tonnes of compostable material each week. Waste that is not recycled is sent to one of Bedfordshire's landfills. Bedfordshire has a landfill capacity for 28.5m tonnes of MSW if current disposal rates are maintained (Environment Agency, 2001).

Bedfordshire imports and disposes of large quantities of waste from neighbouring regions, predominantly London. Some 59,040 tonnes of MSW is imported to landfill in Bedfordshire each week, dwarfing the waste generated in the region. As will be shown in the IWMS technology assessment results in Chapters 7 and 8 this importing of waste has significant impact on performance of the integrated waste management system.

Table 4.1 - Modelled variation of spatial resolution between the Bedfordshire sub-region and the East Anglia Region, based on 2000 data (adapted from Environment Agency, 2001)

Spatial Decision Level	Number of Households	Area (km^2)	Average Transport Distance (km)
Bedfordshire Sub-Region	234,000	1231	19.8
Regional i.e. East of England	2,200,000	20775	81.3

Table 4.2 - Destination of Recovered Materials from Bedfordshire Material Recovery Facilities (King, 2003)

Material	Sub-categories through additional sorting of material	Market destination for Bedfordshire MRF separated material
Paper	Mixed Newspaper and Pamphlets Cardboard White office Mixed office	Shotton Mill, Chester
Metals	Mixed Ferrous Non-ferrous	Al Alcan regional Steel AMG regional
Glass	Brown Clear Green Mixed	Berrymans, Dagenham or S Kirby, S Yorkshire
Plastic	Mixed Plastic PET Coloured PET Clear PVC HDPE	HDPE – Linpac, Castleford PET – Wellman, Belfast, Dublin
Compost		Newton Longville, Bucks

4.2.2 Treatment approach - single process versus multiple process assessment

For an integrated assessment of the waste management system the model needs to be designed to assess the life cycle of waste from generation to disposal not individual processes. A weakness of early waste management models is their limitation to single process technology assessment. The transformation of waste and the uncertainty associated with key technology performance variables means it is unsatisfactory to assess technology in isolation. In the waste industry the impact of a single process can merely transfer the cost of waste further along the system (Downer, 2003). For example, the diversion of waste from landfill to recycling processes can transfer the environmental cost from landfill into transportation emissions (pollution). The model needs to be designed to understand the wider impact within an integrated waste management system not just the performance of individual processes (technologies).

Through developing the model to support the aggregation of different technology types an assessment of the overall impact or net performance of the system can be established. Through designing the model with the ability to vary the rate of implementation of technology (through aggregation) the risk associated with adopting new technology can be reduced. The risk associated with technology can be reduced through adopting incremental technology change compared to dramatic technology change allowing transition costs to be reduced.

4.2.3 Waste Stream & Materials Approach - Multiple waste material modelling versus single waste material modelling

Waste legislation has becoming increasingly targeted towards individual waste streams e.g. the WEEE directive and fridge recycling. As identified in Chapter 3 the model is designed to assess the municipal solid waste stream.

It is proposed that policy will shift towards Integrated Product Policy (IPP) where policy is based upon the lifecycle of products no matter the source with targets set for the reuse and recycling of specific materials e.g. paper. Through reducing the number of waste materials to be modeled the opportunity for technology assessment is reduced. Criticisms of single waste material modeling include:

- Single waste material modelling promotes the separation of individual waste materials making the assumption that separation of the waste is more favourable than no separation.
- Waste technology not requiring separated materials would not be addressed through single material modeling.
- Waste contracts are not tendered for single materials.
- There are often trade-offs between waste materials when formulating waste strategy as some waste materials are prioritized at the expense of others (as described in Chapter 3, section 3.4.2).
- Operational problems of contamination between waste materials could not be addressed through single material modeling.

Technology opportunity can be further affected by the extent of modelling the diversification of waste materials. For example technology performance for paper recycling might be improved through diversification of the paper i.e. there might be sufficient markets to justify the recycling of the office paper or cardboard fractions but not the recycling of lower grade mixed paper.

The model developed here is designed to simulate the number of different household waste collection processes employed in the Bedfordshire sub-region. The result is a 6 waste material model, with waste materials diversified to account only for wastes that are identified to have an existing market potential. The waste material diversification modelled is identified in Table 4.2 above. This trade-off in the design between model simplicity and the simulation of the complexity of a waste management system limits the opportunity to assess technology options. As will be described in Chapter 10 through further development of the model to incorporate additional diversification of waste materials opportunity for technology might be improved and new markets for diversified waste materials identified.

4.2.4 Different Time Frames - Modelling Risk versus Uncertainty

Waste management models reviewed in Chapter 2 concentrated on risk assessment and sensitivity analysis to assess a technology's ability to perform under different environment conditions over time. These assessments are conducted as a second phase of the technology assessment procedure. The uncertainty of the environment should be included in the design of the technology assessment technique i.e. the model design, as uncertainty and risk are different phenomena.

In risk assessment technology is assessed against the probability of something happening (Keeney & Raiffa, 1976). There are other aspects to uncertainty that need to be assessed when evaluating technology performance over time. Environment uncertainty is due to the stochastic (uncertain) and dynamic (evolving over time) nature of the environment (both internally and externally) in which the technology will operate (Ramasesh, 1997). Uncertainty can be an emergence of a decision driver e.g. evolving EU environmental policy. Uncertainty can be the sudden or dramatic change in a technology driver. For example environmental catastrophes can cause sudden changes in strategy surprising and challenging technology performance. Technology assessments should include the ability to assess technologies for surprise and emergent events, not just assess risk based upon probability. If technology can be shown to sustain performance in an uncertain environment it is more likely to overcome the institutional barriers to technology innovation and more likely to be introduced.

Keeney and Raiffa (1976) provide examples into combining measuring both risk and uncertainty. They highlight the use of identifying bounding scenarios to assess decisions in environments of high uncertainty. For decisions based within uncertain environments, bounding scenarios are identified to determine the limits or extremes of an assessment. They identify the likely performance under the external conditions and bound the limits that the technology is assessed within. The scenarios can be weighted to reflect their likelihood of occurrence.

Through designing the model with the ability to vary the rate or implementation of new technology, an evaluation of the different types of uncertainty on technology (system) performance can be established. This provides an assessment of technology performance in a dynamic environment. This addresses a weakness of IWMS models as described in Chapter 2, that assess technology performance in a static environment at a single point in time.

4.3 Summary

The design of the model will affect the ability of the model to simulate the complicated waste management system in the Bedfordshire sub-region of the UK. Through consideration of different approaches to integrated waste management assessment (as identified by EFIEA, 2003) opportunity for new technology will be reduced. As the assessment approaches emerged in part from the design of EU waste policy, the reduced opportunity for new technology can be argued to be as a consequence of policy design.

To maximise the opportunity for new technology assessment within the model it is important to design the model with the capacity to adopt more than one approach to integrated waste management assessment. The next chapter describes the development of the model in Simile Process Simulation Modelling software highlighting practical issues of incorporating these design issues into the physical development of the model.

Chapter Five – Model Development

5.1 Introduction

This chapter highlights practical difficulties of developing an integrated waste management system model. It discusses the difficulty in designing a model to consider economic, environmental, social and operational factors as identified in Chapter 2.

Given the range of influences on model design (as identified in earlier chapters) a combination of simulation and process modelling is required. Process simulation modelling is a way of representing a system, its activities, the logic of interaction between the activities and predicting future performance through simulation (Javaid, 2002). It is an emerging field and the lack of Process Simulation Modelling software influenced the design of the model. Various software packages were identified as possibilities including Stella, Geographical Information Systems (GIS), C++ and Visual Basic programming.

This chapter describes the development of the integrated waste management assessment model in the selected Simile software. Simile is a software tool useful for designing, building and running simulation models in environmental science (Simulistics, 2004). It adopts a diagram-based language for designing models, including both System Dynamics and object-based concepts. Simile allows modular model construction. An example of an application of Simile is the Forest Land Orientating Resource Envisioning System (FLORES) project. This is an international programme of research aiming to improve the livelihood of the rural poor at the forest margin. The FLORES model is used to investigate the likely impact of alternative policy options and land management decision making.

5.2 Model Development in Simile

A key component of a simulation process model is the identification of a flow unit. Within the model the unit of flow selected is 1 tonne of collected MSW per week. (The composition of the MSW in the case study Bedfordshire region is described in the Appendix). This is selected as costs associated with MSW are often displayed in £ per tonne e.g. the Landfill tax is calculated in terms of £ p t. Tonnes are used to describe the processing rates of technologies and the availability of landfill space in various data sources e.g. tonnes per annum. As the model is designed to replicate the waste management system in the UK £ p t is used though this can be easily converted to Euros by multiplying the results by an appropriate exchange factor (approximately 0.6, at May 2003 exchange rate).

A weakness in adopting £ p t as the unit of flow is the failure to recognise the impact of the physical characteristics of waste on technology performance. For example Seaton et al. (2003) showed that in fridge recycling, the volume of fridges affects the storage, transportation cost and technology performance. The physical characteristics of waste vary as waste is transformed by the various processing technologies in a waste management system. In the model design, a trade-off occurs between the ability to simulate the impact of the physical characteristics of waste composition on technology performance and complexity of model. Modelling such characteristics as the degradation of waste is addressed in the costing of waste technology section later in the chapter.

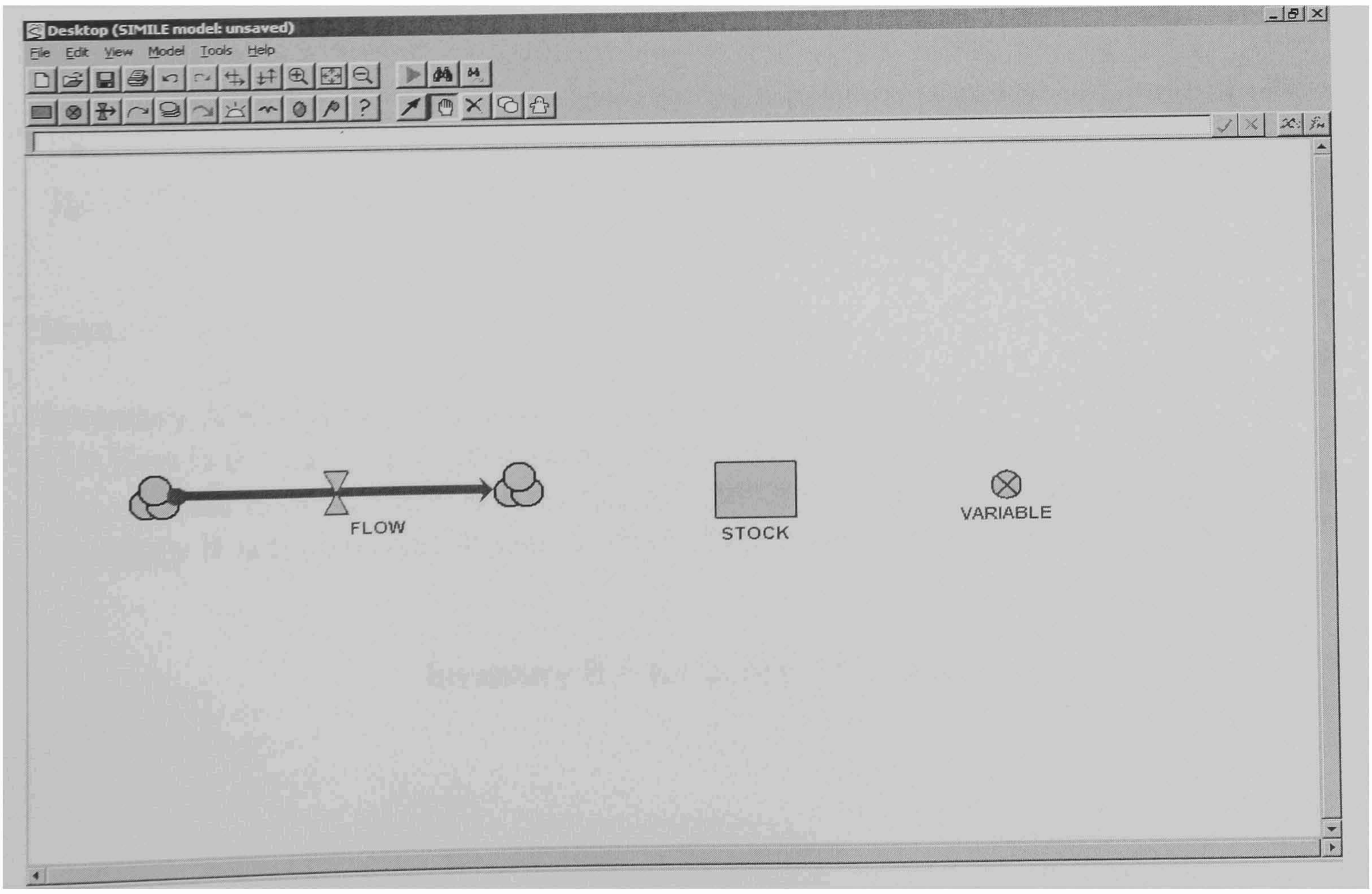
An alternative unit of flow might have been kilograms per household (Kg p hh). With waste charging operational in other EU countries and being discussed as a future waste strategy policy in the UK, the unit of flow of kg per hh might be a future development of the model and is discussed further in Chapter 10.

Simile adopts a combination of manual and automatic modelling. In the waste industry the complexity of options within a strategy makes it difficult to create a fully automatic model. Through adopting a manual modelling approach greater flexibility is gained in assessing technology options in the uncertain environment over time. The modelling approach allows exploration of the relationships and barriers to new technology.

5.3 Modelling the Integrated Waste Management System in the Simile software.

Simile works through a series of stocks, flows and variables. A stock is an inventory of material at that point and time in the system. A flow identifies the direction of flow material between stocks. Variables are factors that convert the flow due to transformation of flow or through control of the flow (See Figure 5.1 - The Classification of System Components in Simile).

Figure 5.1 - The Classification of Simile Components

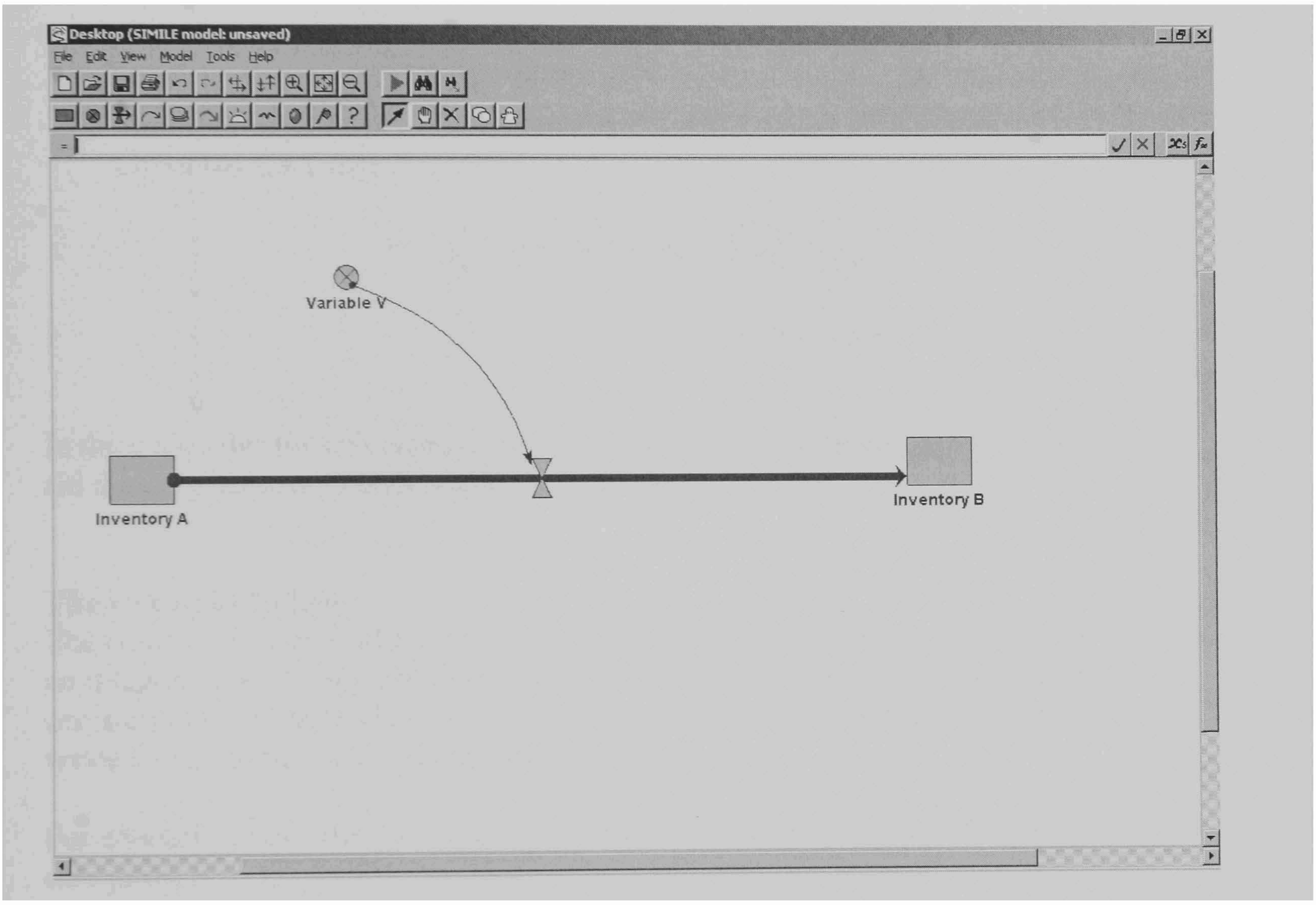


Transformation of Flow

Transformation of flow is where the flow is transformed by a variable (factor) along its flow. Within an integrated waste management system these types of variables include the rate of source separation, the recycling rate and the fraction of hazardous waste generated from an Energy from Waste facility.

For example:
To calculate the amount of glass waste collected via civic amenity sites, Figure 5.2 shows how this would be represented in Simile.

Figure 5.2 Transformation of Flow represented in Simile



Here,

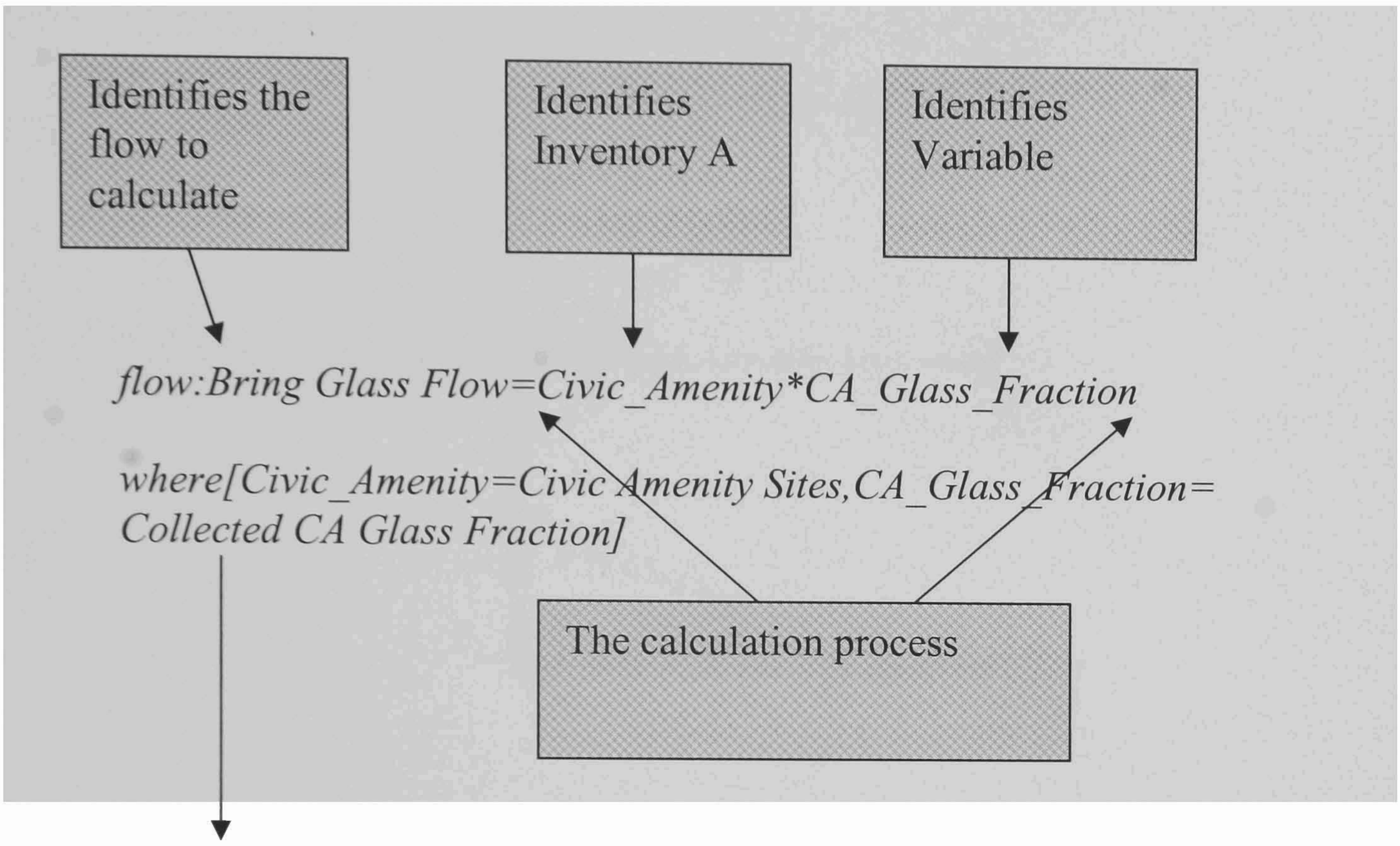
Inventory A would be the total amount of waste collected,
The flow is the amount of glass collected via the civic amenity site,
The variable is the fraction of the civic amenity site collected waste that is glass,
Inventory B is the amount of glass collected after the time period of assessment.

Inventory B = Inventory A*Variable

With the flow being controlled by the time period of assessment and whether the variable is fixed or not.

In simile this is represented by code:

Figure 5.3 Simile Code to represent Transformation of Flow



```
flow:Bring Glass Flow=Civic_Amenity*CA_Glass_Fraction

where[Civic_Amenity=Civic Amenity Sites,CA_Glass_Fraction=
Collected CA Glass Fraction]
```

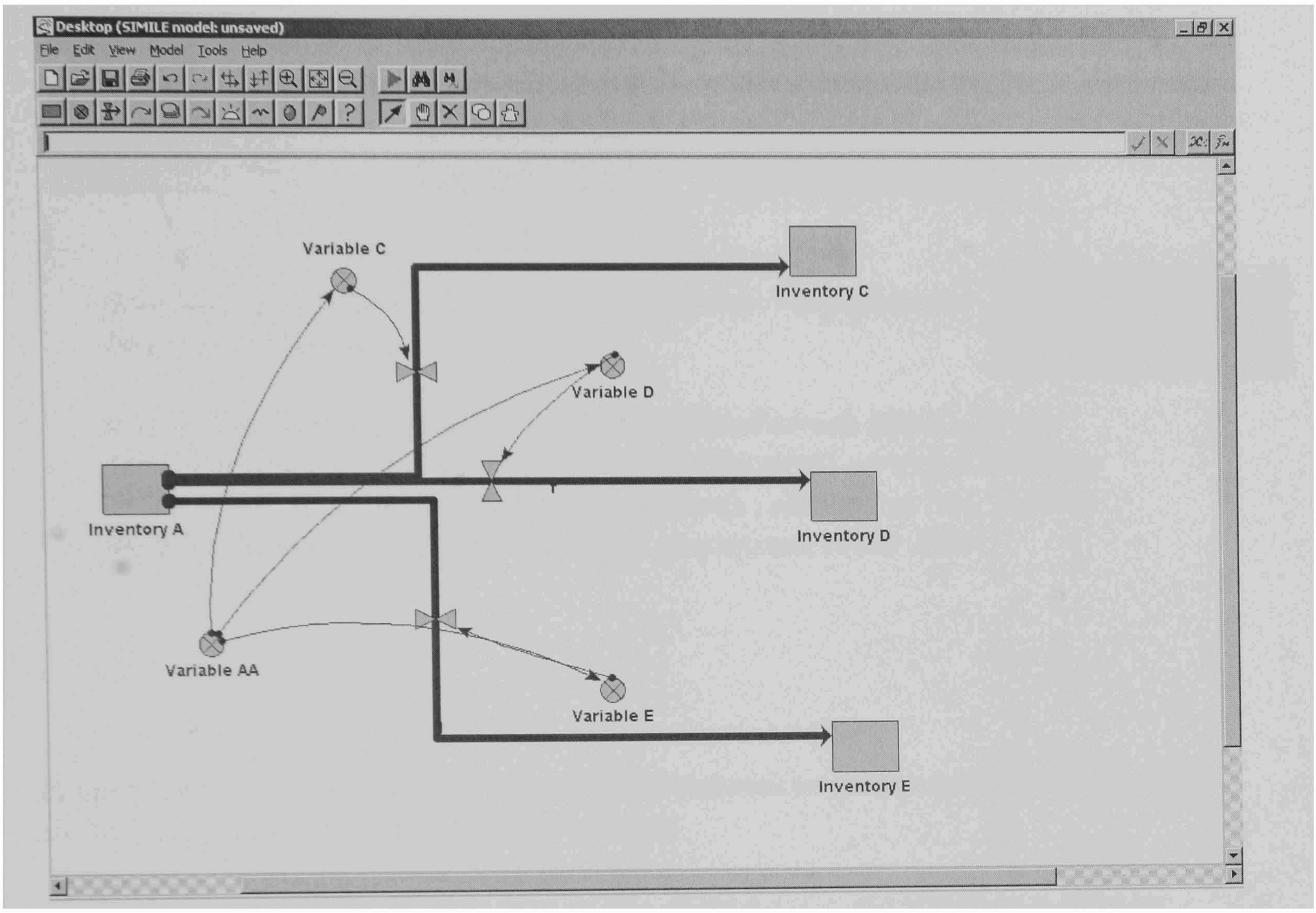
In the code after the calculation process definitions/descriptions of each component aid the programmer to understand the process.

The Control of Flow

The control of flow is where a variable controls the flow between inventories. Within an integrated waste management system controls of flow variables include the decision to treat waste via different process or the extent to which to diversify the waste stream at the materials recovery facility.

For example, to calculate the amount of waste separated into the different metal categories if metal sorting via eddy currents and magnets becomes available at the MRF. Figure 5.4 shows how this would be represented in Simile.

Figure 5.4 Control of Flow represented in Simile

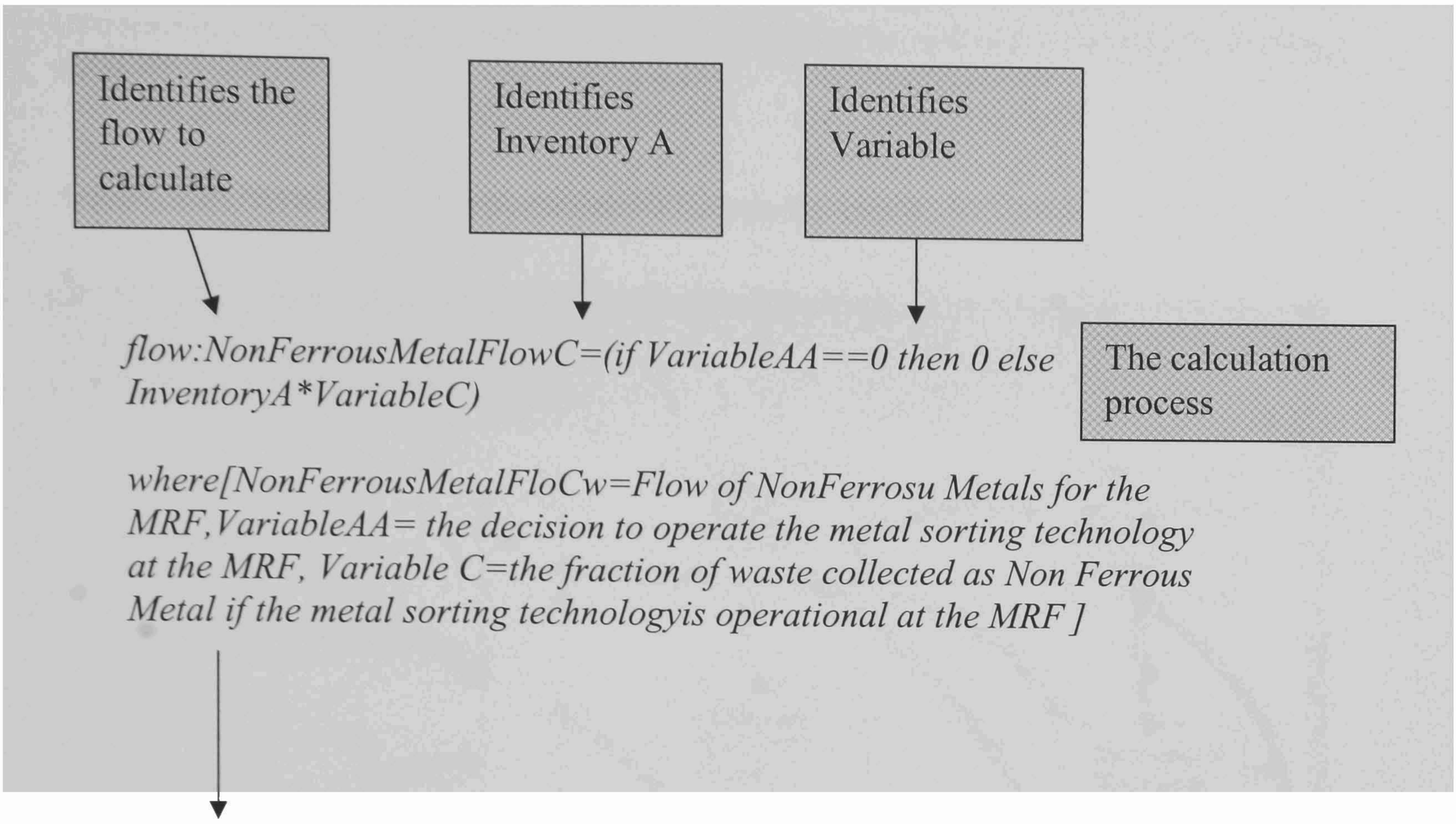


Here,

Inventory A equals the amount of mixed metal waste flowing through the MRF,
Variable AA is the control switch which determines whether metal diversification is operational or not.
Variable C is the fraction of waste sorted as Non Ferrous metal
Variable D is the fraction of waste sorted as Ferrous metal
Variable E is the fraction of waste sorted as mixed metal
Inventory C is the amount of Non Ferrous Metal
Inventory D is the amount of Ferrous metal
Inventory E is the amount of mixed metal

If the metal sorting is operational and the metals are sorted into the different diversified waste materials i.e. the sorting technology is turned on, the Simile code is represented:

Figure 5.5 Simile Code to represent the Control of Flow



```
flow:NonFerrousMetalFlowC=(if VariableAA==0 then 0 else
InventoryA*VariableC)

where[NonFerrousMetalFloCw=Flow of NonFerrosu Metals for the
MRF,VariableAA= the decision to operate the metal sorting technology
at the MRF, Variable C=the fraction of waste collected as Non Ferrous
Metal if the metal sorting technologyis operational at the MRF ]
```

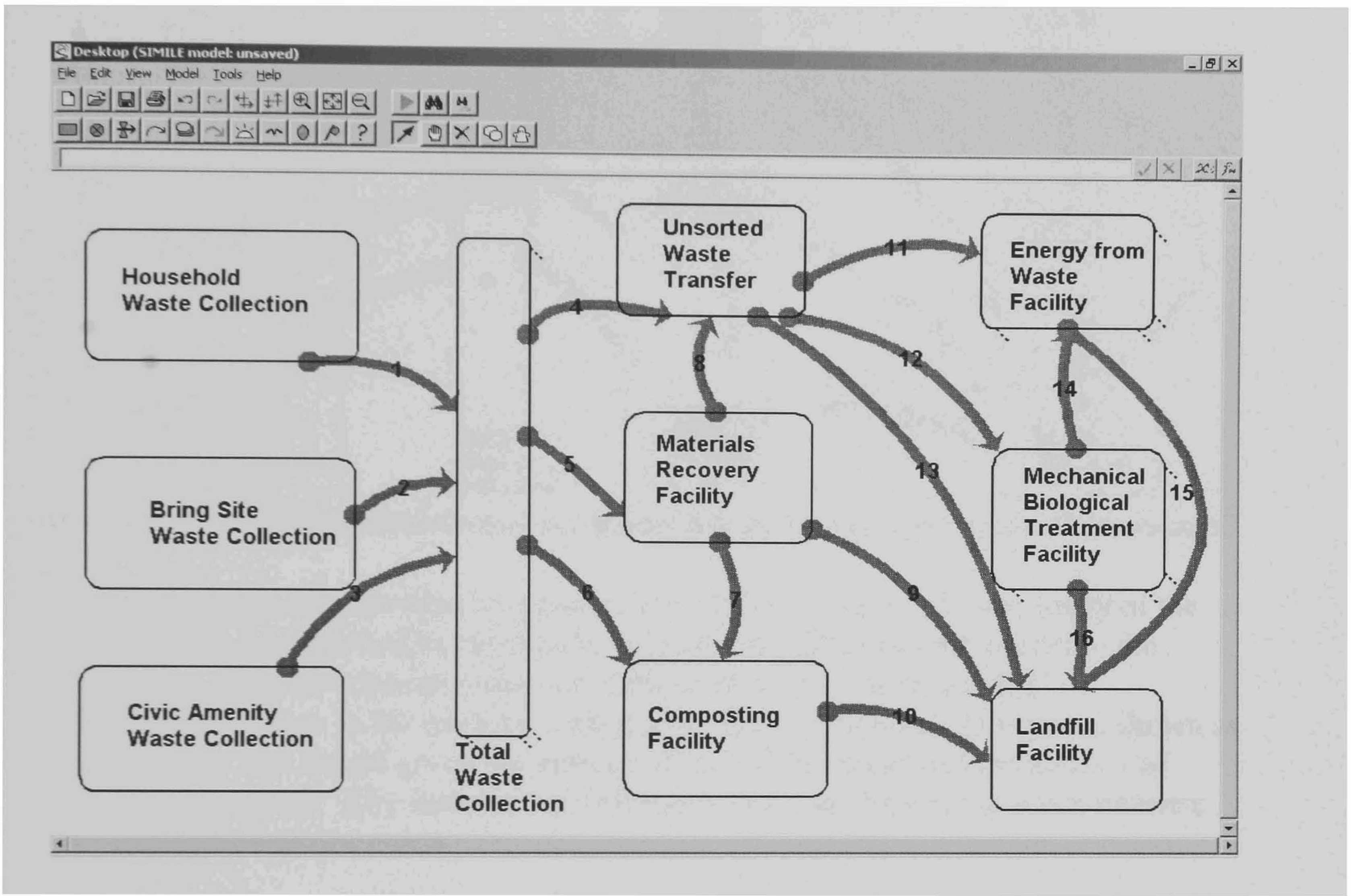
In the code after the calculation process definitions/descriptions of each component aid the programmer to understand the process.

(In the further examples of code used in this chapter the same structure is used to describe the code as identified above.)

The model is designed to map the flow of waste from generation through treatment and recycling technology to disposal. Figure 5.2 shows the model structure within the waste strategy model. This structure is based upon the waste strategy in the Bedfordshire sub-region (as described in Chapter 4) and allows the investigation into the opportunity for technology innovation. Each envelope represents an individual sub-model that characterises a process within the waste management system. Each sub-model uses a costing sub-model to identify the cost of transferring 1 tonne of waste in £ per t through the technology sub-model. These costs are aggregated to find the net unit cost of the integrated system. The cost is based upon the economic, environmental and social cost of technology. The arrows between the envelopes represent the relationships between the different processes that occur within the model. These flows are influenced by the relationships between the technology drivers, conflicts and barriers in the UK waste industry. The sub-models represent the waste process technologies described in Chapter 3. The variables within each sub-model are listed in the Appendix .

In the model each sub-model represents the total availability of that resource in the given spatial area, it does not account for every single facility but aggregates the availability of each technology. This approach to modelling is used to simplify the model and help create a structure that allows easy assessment between different spatial resolutions. To model different spatial resolutions the model is merely supported by different data and does not require expensive and time-consuming redevelopment. Another advantage of modelling in this way is the ease with which technologies can be changed and integrated within a system. The extent of the system integration can be easily assessed through plugging in and out different technology options.

Figure 5.6 - The Model Structure for Household Waste



The sub-models are split into four types of sub-models:

- Generation Sub-Models (G) (Figure 5.8)

In these models the quantities and amounts of waste (resource) are identified.

- Process Sub-Models (P) (Figure 5.9)

In these waste (resource) is transformed through a technological process.

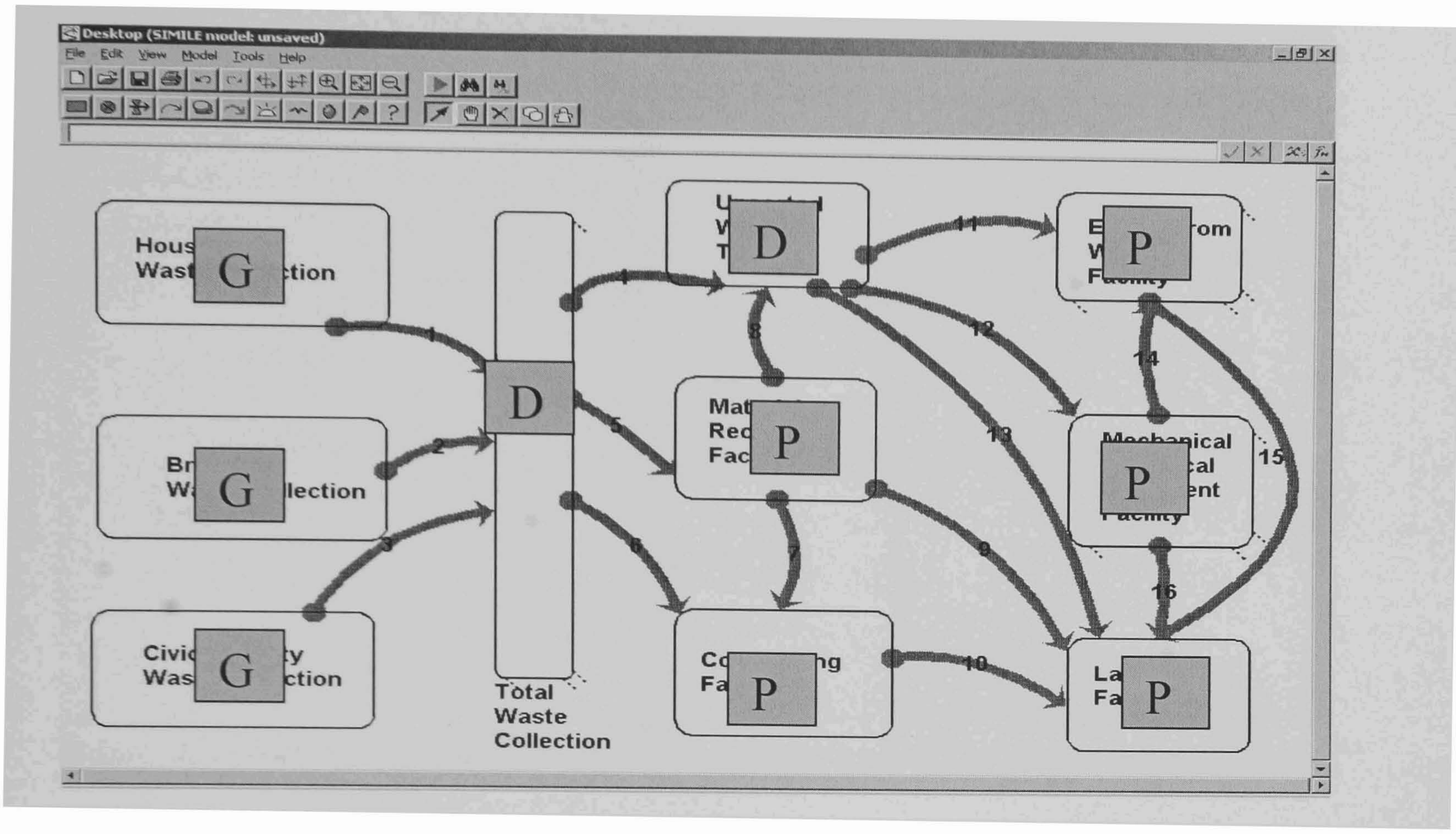
- Decision Sub-Models (D) (Figure 5.10&5.11)

These define the decision options available within an integrated system such as the timing of technology change and the technology strategy.

- Costing Sub-Models (Figure 5.12)

These models calculate the costs associated with flow of 1 unit of waste (resource) through the model.

Figure 5.7 Model Structure with Generation, Process or Decision Models

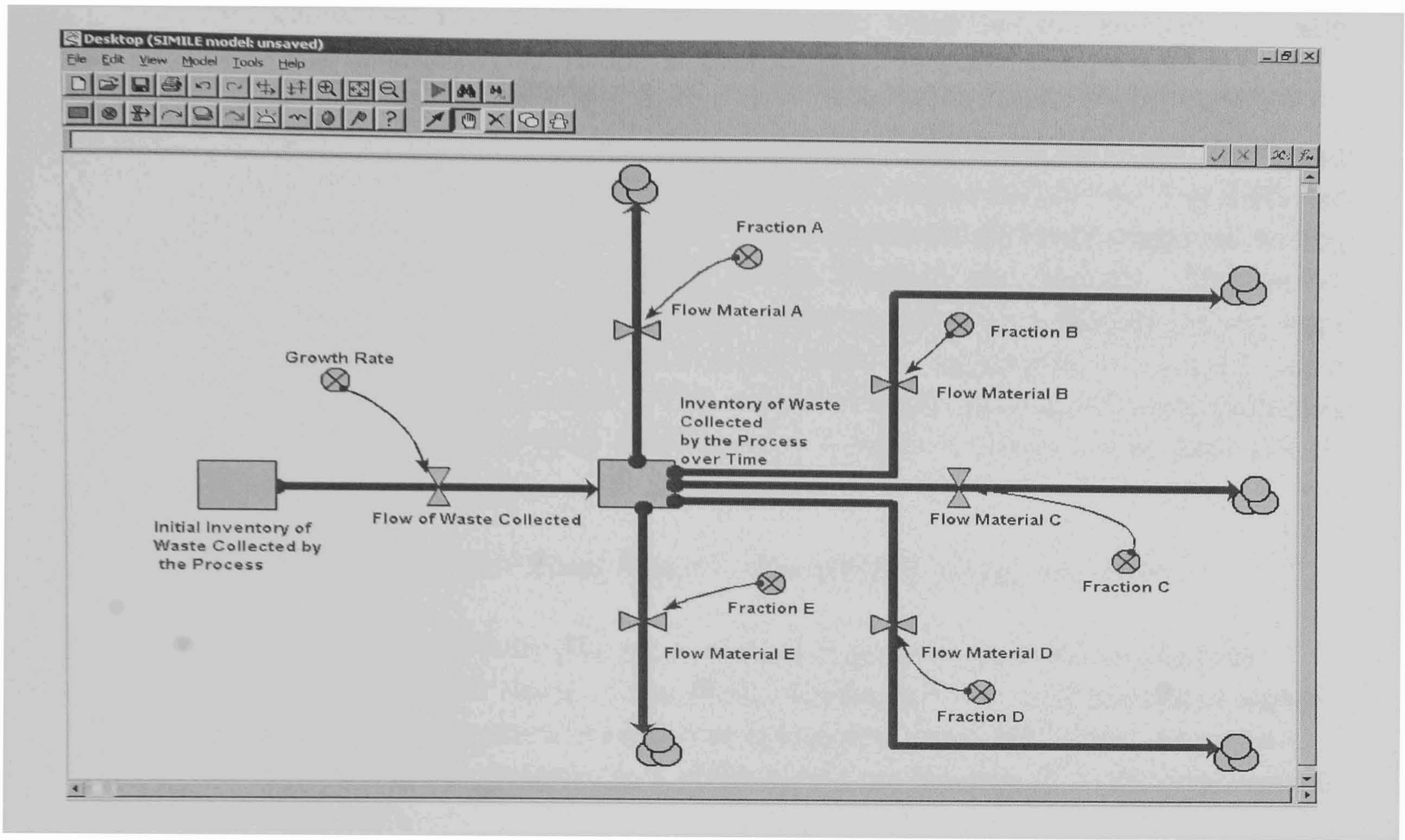


The sub-models are described in greater detail below. Given the complexity of the sub-models, as identified by the number of variables listed per sub-model in the Appendix. The descriptions below are used to identify a more 'generic' or 'structured' pattern to the model development. Each technology sub-type is shown as an 'abstract' sub-model given the intricate detail of the model and the number of variables involved. Key features and influences on modelling in the waste industry are identified and discussed.

5.3.1 Generation Sub-Models

As identified in Chapter 4, waste is collected in the Bedfordshire region via three processes i.e. household collection schemes, bring sites and civic amenity sites. The model represents the collection of waste via each process. The household waste collection, bring sites and hwrc (civic amenity) sub-models as highlighted in Figure 5.6 adopt the structure of a Generation sub-model. These models include a simple calculation to identify the amount of waste generated by the respective collection or recovery methods. Figure 5.8 displays the structure of these waste generation sub-models. These generation sub-models adopt the Transformation of Flow technique as described earlier. To demonstrate how these sub-models were designed and operate is easiest through an example.

Figure 5.8 **'Abstract' Generation Sub-model**



For example, to calculate the amount of glass waste generated from household waste collection. The calculation process is split into various steps which are highlighted as designed features in Simile in Figure 5.8.

1. Identify the total waste generation in the region by household waste collection. As described in Chapter 4 this is identified from the Environment Agency's Strategic Waste Management Assessment reports (2000). In Figure 5.8 this is represented in Simile as the Initial Inventory of Waste Collection by the Process.

2. Identify a growth rate for the waste generation. An average growth rate of 2.7% was used for all waste generation models (Environemt Agency, 2001). This is represented in Figure 5.8 as the variable growth rate.

3. Calculate the growth in waste generation over the time period of assessment. This calculation process is located in Figure 5.8 at the Flow of Waste Collected with the Inventory of Waste Collected by the Process over time marking the result.

   The code in Simile to represent this calculation:

   *flow:Total Waste Collected=Growth_Rate*Initial Inventory of Waste*

   where [Total Waste Collected=The inventory of waste collected by the household collection scheme over the time period of assessment, Initial Inventory of Waste=the inventory of waste in 2000 in the region, Growth_Rate=The forecasted increase in waste generation, 2.7%]

The calculated inventory of collected waste identifies the amount of waste generated after the time period of assessment.

4. Calculate the amount of glass waste within the total waste collected. As Figure 5.8 shows the total waste material is then split or diversified into four different waste materials i.e. A, B, C and D. These represent different materials within the waste stream such as Paper, Glass, Plastics and Metals. The model calculates the total amounts of each waste material as a fraction of the total waste stream. These fractions (values) need to aggregate to 1 so all waste inflow is tracked to outflow. The values of each fraction of waste collected are calculated based upon Bedfordshire County Council waste data (BCC, 2002).

   *flow:HH Glass Flow=Total Waste Collected*HH_Glass_Fraction*

   where[HH Glass Flow=The total amount of glass collected over the time period in tonnes per week,, Total Waste Collected= the total amount of waste collected in the assessment region in tonnes per week, HH Glass_Fraction= The fraction of the waste stream collected by the household collection method that is glass]

The generation sub-models identify the waste materials that are recovered by the respective methods e.g. Paper, Glass, Plastic, Green, Metal and Textiles.

Time variables are included in the generation sub-models. The time variables allow the timing of variation to strategy to be controlled. In Bedfordshire, green waste (household kitchen and garden waste) began collection via source separation schemes in February 2003. (Green waste collection in the Luton area of the Bedfordshire sub-region began earlier in 2001.) Using the time variable, the model is set up to reflect these changes by varying the fractions of the waste materials recovered. For example when the green waste is collected as part of the source separation scheme, the fraction of bulk waste collected is reduced depending on the amount of green waste recovered.

For example to calculate the variation in bulk waste fraction.if 88% of household collected waste is unsorted in 2000 and 2.5 % of green waste will be collected by a new green bin collection method in 2001-2 and 5% collected in 2002-3 (Recycling & Waste World, May 2003).

Here the variable the fraction of unsorted bulk waste is displayed in code as:

variable:Unsorted Bulk Fraction=(if Green_Time>104.1&&Green_Time<156.1 then 0.855 elseif Green_Time>156.1 then 0.83 else 0.88)

where[Unsorted Bulk Fraction= the fraction of the waste stream that is collected unsorted, Green_Time=the time from the year 2000 in weeks, therefore after 2 years i.e. 104 weeks when the green waste collection scheme *is initiated the amount of unsorted bulk waste fraction is reduced by he 2.5% that is now collected as green waste].*

Other key issues to consider in waste generation modelling in the waste industry include:

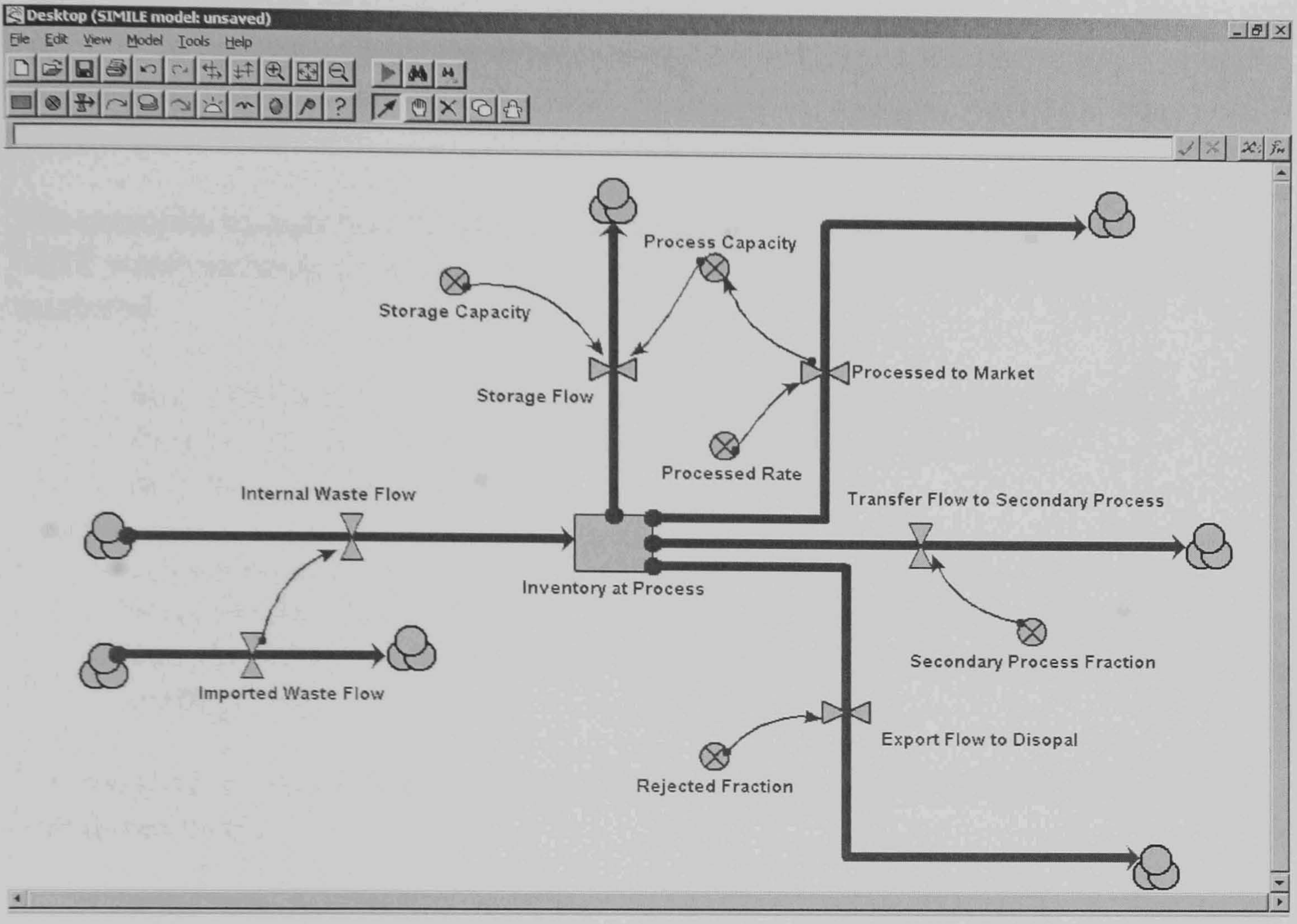
- How variation to the rate of generation and collection of waste is modelled e.g. weekly, daily, fortnightly collection? The Simile model is designed to operate on a weekly basis as waste is usually collected once a week in the Bedfordshire sub-region. The model has the capability to vary the timing of waste collection and a decision to simulate variation in this way would be determined by the scenarios to analyse. The technology scenario options modelled is described and justified in Chapter 6.

- How is the handling of waste materials with health and safety considerations addressed within the model? The health and safety issue relating to waste management is becoming an increasingly important issue as waste undergoes transformation through processing as described in Chapter 3. For example does the manual separation of waste at a MRF pose a potential health issue to the sorting workers? To reflect the health and safety problems created by processing of waste each technology sub-model could have an additional cost incorporated into the model design. At present insufficient data and research in this area means such values are not available.

- How does waste composition change in response to varying socio-economic conditions and temporal conditions? Different model scenarios were analysed to reflect the temporal changes in waste composition e.g. to represent waste composition variation at Christmas. Given the timescales involved in the modelling patterns (i.e. 20+ years) they did not display any significant impact on the overall performance of technology. As was described in Chapter 3, it is difficult to predict how waste composition will vary over time given the uncertainty of environment. Variation to waste composition over time is modelled using the predictions of Tucker et al. (2003) as described in Chapter 3. This variation in waste composition over time is modelled through applying timing constraints to variation of waste material fractions as described earlier in the equations for variation of Bulk Waste example.

5.3.2 Process Sub-models

Figure 5.9 'Abstract' Process Sub-model



The process sub-models represent the technologies that transform the waste. The processing technologies modelled include the Materials Recovery Facility, the Composting facility, the Mechanical Biological Treatment 'Ecodeco' facility, the Energy from Waste 'Pyrolysis' facility and the Landfill facility. These technologies have been described in Chapter 3. These processes all transform the waste into different products whether to recover value or if there is no market value to send to disposal. The processing technologies all work on the same principle that the resource is fed into the sub-model from two sources. The first source is waste generated and collected within the region of assessment. The amount of internal waste inflow into each waste process sub-model is determined by Decision Sub-Model A which is described later in the chapter. The second inflow of waste into these process sub-models is waste imported from outside of the assessment region. The two waste flows are aggregated to identify a total waste flow for the process sub-models.

The waste flow is then processed within the sub-model into four new flows as highlighted in Figure 5.9. These are identified as:

i. Waste processed and sent to market
ii. Waste rejected and sent to landfill
iii. Waste stored at the process facility
iv. Waste transferred after processing to a secondary treatment process.

The transfer of waste to each of these new flows depends on variables such as:

i. The processing rate and capacity of each process
ii. Storage capacity
iii. The fraction of waste rejected by the process technology
iv. The fraction of waste sent to a secondary waste process

These relationships are represented in Simile as follows.

For example, to calculate the flow of waste processed and transferred to market by a MBT waste technology in tonnes per week a transformation of flow technique is modelled.

> *flow:MBTtomarket=(if Inventory_at_MBTtech>Processing_Rate then Processing_Rate elseif Inventory_at_MBTtech==0 then 0 else Inventory_at_MBTtech)*
>
> *where[Processing_Rate=The maximum weekly processing rate in tonnes per week for the MBT technology, Inventory_at_MBTTech=total inflow of waste into the MBT technology i.e. the aggregation of the internal and external waste flows]*

To calculate the flow of rejected waste sent to landfill from the MBT technology in tonnes per week

.

> *Flow:Rejected Flow to Landfill= Rejected Fraction*Inventory_at_MBTtech*
>
> *where Rejected Flow to Landfill = the flow of waste rejected as unsuitable for market, Inventory at MBTtech = the total amount of waste processed by the MBT technology]*

To calculate the amount of stored waste if storage capacity available a control of flow technique is modelled.

> *flow:MBT Stored Waste=(if MBT_Storage_Capacity==1 then Inventory_at_MBTtech*Stored_Fraction else 0)*
>
> *where[MBT Stored Waste = the flow of waste to storage at the MBT facility, Stored_Fraction = the fraction of waste that can be stoired]*

Each process technology in the waste case study has individual characteristics that need to be addressed in the modelling design. The interaction between these operational demands/constraints and the human socio-economic factors affects the evaluation of technology performance. Those described here only relate to material flows, issues relating to costs will be addressed in section 5.3.5.

- How is technology shutdown time either for cleaning or system failure modelled? Technologies such as EfW are not operational all year round as they shutdown to be cleaned, inspected or as a consequence of technology failure e.g. accidents. Within the model shutdown time is not modelled as the operating rates used are calculated from annual operating capacity. Therefore the operating rates are average operating rates per week over the year. Technology shutdown time can be modelled through temporarily closing technology and diverting waste to storage facilities. This type of model scenario can be used to assess uncertainty due to unforeseen or dramatic events as described in Chapter 4, section 4.2.4. Through modelling these types of scenario a greater understanding of the trade-off between reliability of technology and technology performance is identified.

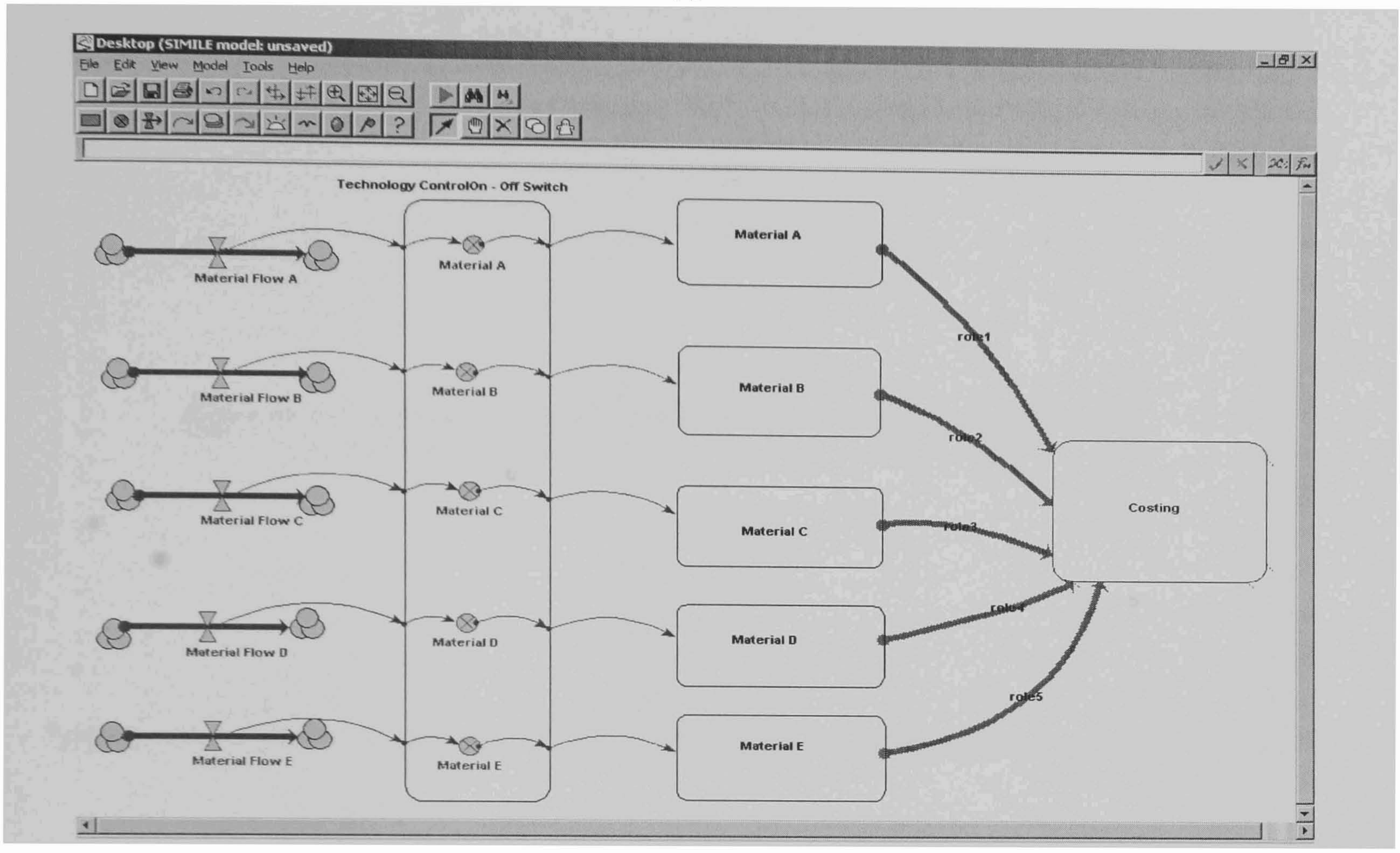
- How is the relationship between internal and external source waste modelled? Waste technology often includes imported flow of resource to recover value in their process. For example in the Bedfordshire sub-region due to favourable geological conditions and extensive landfill resources waste is imported from outside the sub-region (particularly London). This affects the costing of technology as different gate fees are applied for processing the waste depending on its origin. Waste imported creates revenue whereas waste generated within the internal region is at a cost to the system. The technology processes modelled have both internal and external waste flow inputs into the processes and different cost variables as will be discussed in the Costings sub-model. As highlighted in Chapter 4 this importing and exporting of waste between spatial regions across 'artificial' barriers to technology is an important factor in technology performance. It is discussed further in determining the scenarios to model in Chapter 6.

- How is the relationship between technology excess capacity versus storage modelled? A key issue in understanding the performance of technology is identifying the efficiency of the technology. How much efficiency is lost by redundancy of the technology, how much storage is not utilised? The model can be used to explore the relationship between technology efficiency, capacity and storage through varying the scenarios analysed to reflect uncertainty of these variables.

- How is the technology efficiency affected and modelled to reflect variation to the waste stream composition? The operating efficiency of technology can be affected by the waste composition e.g. the composition of waste composted affects the quality of the compost produced. This is reflected in the model by increasing the rejected fraction of waste from technologies. Data identifying the extent to which the waste technology is affected by waste composition is required. Depending on the technology this can be poorly understood, therefore the efficiency of the technology is another variable to consider when modelling for uncertainty.

5.3.4 Decision sub-models

Figure 5.10 'Abstract' Decision model type A



Decision sub-models link the relationships between the Generation sub-models and the Process sub-models. In the waste strategy model there are two decision sub-models. Decision sub-model type A relates to the sorted collected waste and Decision sub-model type B relates to the collected unsorted bulk waste.

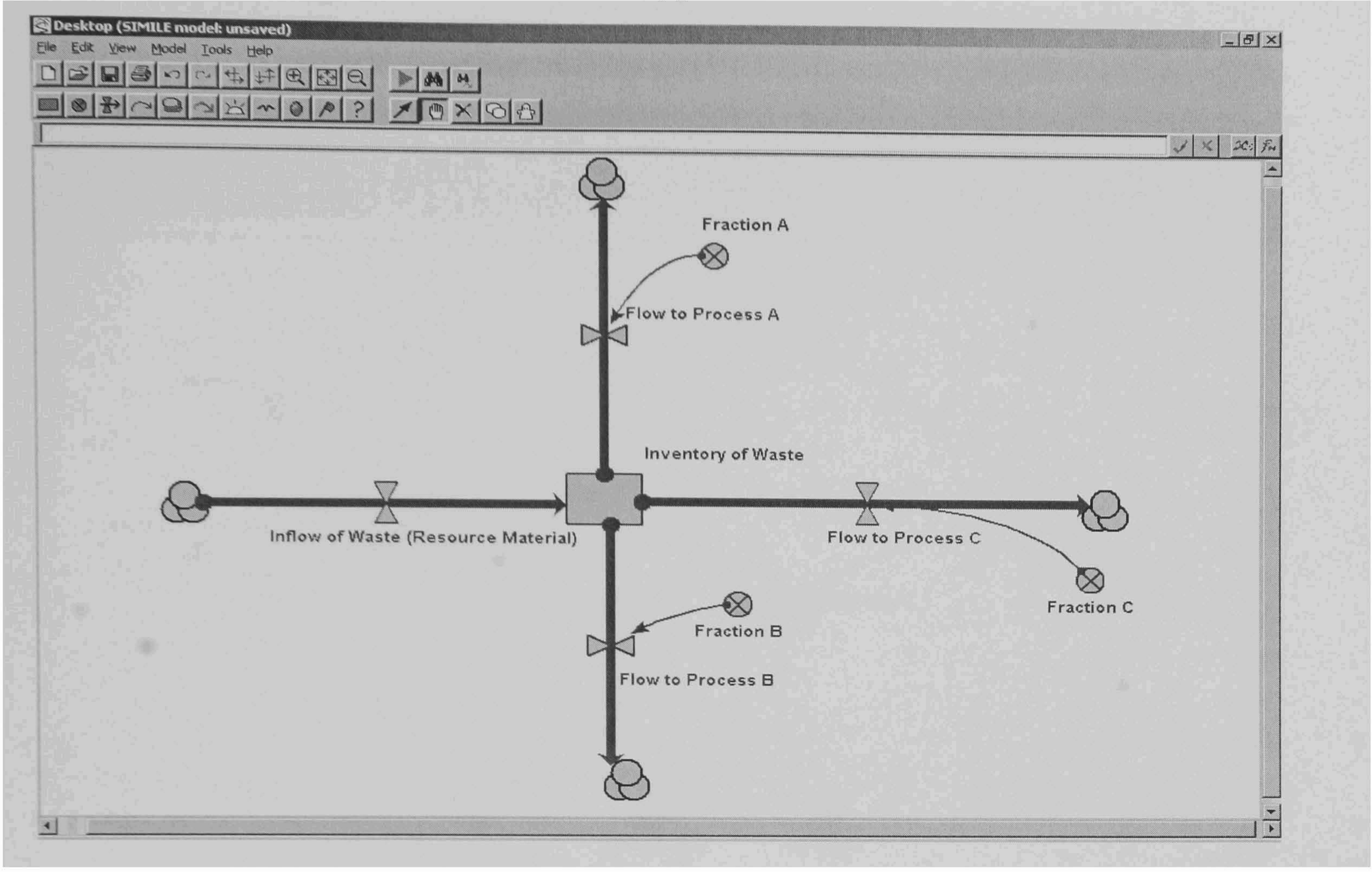
Decision sub-model A Figure 5.10, transfers the sorted waste and is linked to the MRF technology. It is used to identify the diversification (sorting) technologies that are operated at the MRF facility. Here waste can be further diversified or bulked depending on the scenario modelled. The model allows diversification of waste materials as the setting of legislative targets for specific waste materials i.e. the biodegradable waste means that further understanding of individual waste material flows is needed. It operates by turning waste flows and sorting technologies available at the MRF on/off i.e. a control of flow technique.

For example to calculate the fraction of paper waste that is recovered as Newspaper at the MRF

variable:Newspaper Fraction=(if MRF_PAPER_SORTING_CONTROL==1 then 0.4 else 0)

where[MRF_PAPER_SORTING_CONTROL=the decision to adopt paper sorting at the MRF or not if paper sorting is operation then the fraction of paper waste collected as newspaper is 40% of the paper stream else 0% of the paper stream is collected as newspaper as paper is all mixed]

Figure 5.11 'Abstract' Decision Model type B



Decision sub-model B Figure 5.11 relates to the unsorted collected waste that is currently sent to landfill. In order to represent variation to strategy the decision sub-model allows this waste to be redirected to other process technologies such as EfW or MBT technology and allows the timing of the diversion to be varied. The quantity of waste diverted is calculated as fractions of the waste stream. The flow of unsorted waste through the Unsorted Waste Transfer sub-model allows waste to be transferred to further treatment or disposal technology. The sub-model can control the timing of transfer and the destination of transfer. These are viewed as key decisions in waste strategy plans as it is often in these decisions that the conflict between the private waste companies and the strategic objectives of policy (as identified in Chapter 2, Table 2.2) becomes relevant. For example as part of the Landfill Directive all waste needs to be pre-treated before disposal thus a decision has to be made on the treatment of unsorted waste at this point in the system before disposal. The decision identifies a key point in the system where a decision affects the need for the development and investment in technology. As such the scenarios to model identified in Chapter 6 focus on this decision point in the waste management system.

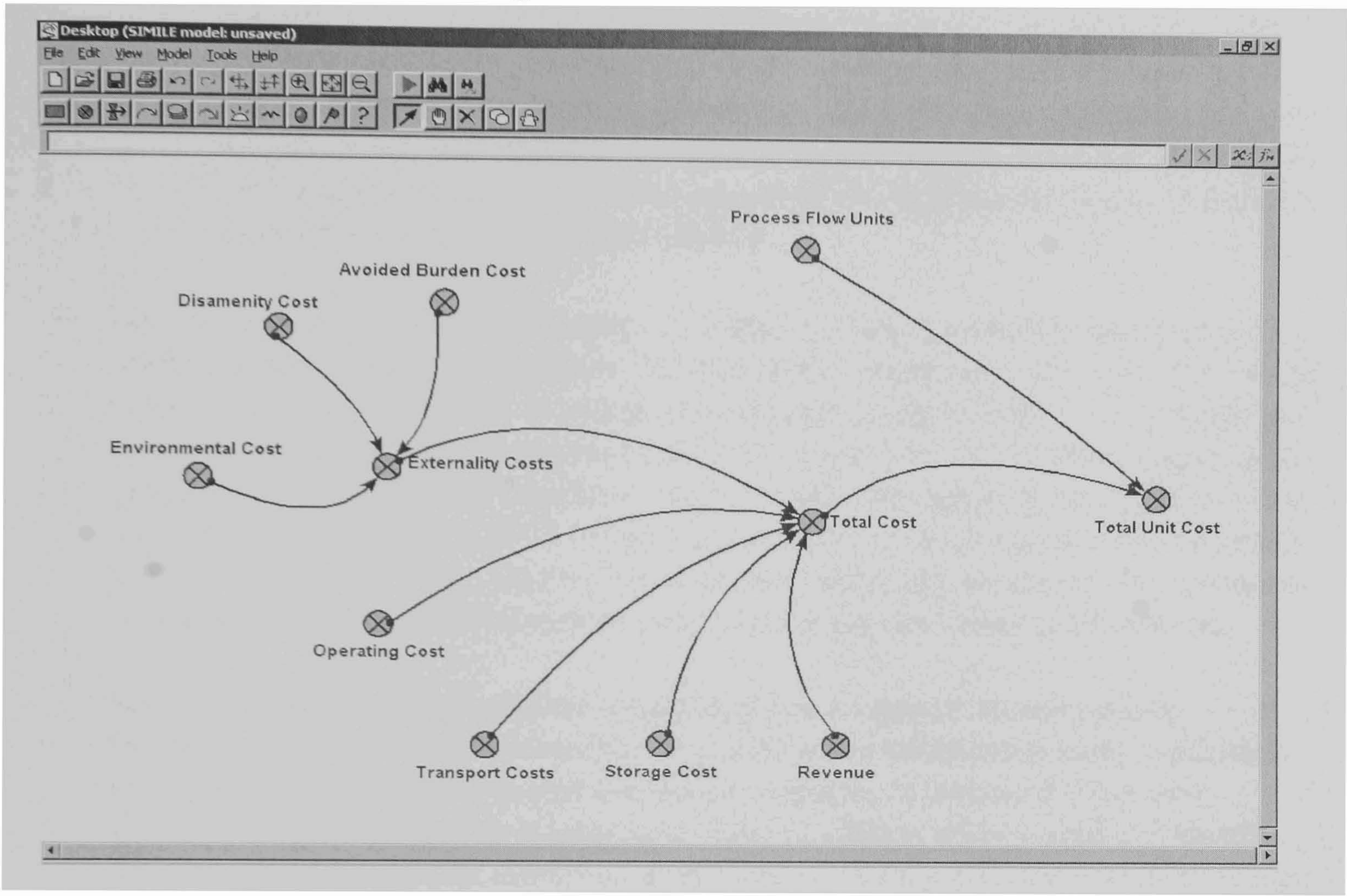
For example, to transfer 30% of unsorted collected bulk waste to a new technology that becomes available after 310 weeks.

variable:New Tech Diversion A=(if Strategy_Time<310.1 then 0 else 0.3)

where[New Tech Diversion A = the fraction of the unsorted bulk waste transferred to the new technology, this is 0% up to 310 weeks and 30% after 310 weeks, Strategy_Time=The time from 2000 in weeks]

5.3.5 Costing sub-models

Figure 5.12 'Abstract' Costing Sub-model



The model calculates the net unit cost of the system for varying waste strategy. Costing sub-models are subsidiaries of the waste generation, processing and decision sub-models. Figure 5.12 displays the different types of costs included:

- Financial Costs – these are the financial cost of transferring 1 unit of waste through the sub-model process. They are the operating cost and capital cost of a particular waste collection or treatment process over the lifetime of the technology. The costs are not the gate fees (gate fees are the costs needed to recover value from the technology over the lifetime of the technology). Capital costs for existing technology are already sunk and therefore do not figure. Capital costs of new technology are identified in £ per capacity of technology. The capital costs of the technologies were identified from various sources including both published and commercially sensitive data.

- Transport Cost – the costs associated with transporting waste were difficult to obtain. Various sources were identified but the results were not consistent. Transport costs are affected by a number of issues not just distance e.g. the number of drivers required, the time to reach a destination, traffic, route, speed limitation and the Working Time Directive (Downer, 2003). Transport costs were calculated in relation to distance, size of vehicle and composition of waste load. Transport costs used in the model use a stepped structure rather than a linear cost in proportion to distance in an attempt to consider the other issues such as driver time etc on cost. Distance between different technology processes of the waste system were identified through various methods:

    - Known distances were modelled e.g. the distance from a MRF facility to a reprocessing facility.
    - Cumulative and average distances of waste collection rounds were identified by the WISARD assessment report for Bedfordshire (BCC, 2002).
    - When varying the spatial resolution between the base condition to neighbouring and regional levels, average distances are calculated as the radius of the surface area of the spatial level. Surface areas were identified through the use of CASWEB (2003).

- Revenues – as identified in Chapter 2, Table 2.1, the uncertainty associated with market prices creates difficulties in evaluating waste systems. In the waste industry the market price is often constrained to an extent by contracts and agreements that can last from individual shipments to years, this uncertainty in the market price is difficult to simulate. In the model the market prices used were the market prices in August 2003 using Letsrecycle.com as the source of the prices. The market prices were frozen but scenarios were run to assess the impact of variation of market price on system performance (as described in Chapter 8).

- Storage Costs – Each processing technology has a capacity to store waste materials either while the technology is shutdown or when processing capacities are exceeded. Within the model the storage capacity is usually 4 times one week's processing capacity (Gascoigne, 2003) as this is widely used in industry. The storage of waste was identified as the cost of storage plus the cost of moving the waste in and out of the facility.

- Land Purchase Costs - The cost of buying land for new facilities was not included in the costs. This is partly due to the variation and uncertainty in land prices depending on location of facilities and the objective of waste companies to build future waste facilities on existing landfill sites (Lowe, 2002). This removes the need to purchase new land whilst enabling new facilities to be more favourable to planning applications given the established waste management facilities already on the sites. Table 5.1 identifies the land area requirements of the respective technologies should costs be applied per hectare of land.

Table 5.1 - Land Requirements by technology (source: Gascoigne, G, Shanks Waste Group, 2003)

Technology	Capacity	Land Area Required
Materials Recovery Facility	85ktpa	0.75ha
Composting	20ktpa 50ktpa	0.5ha 1ha
Energy from Waste – Pyrolysis	60ktpa 120ktpa	3.5ha 4.1ha
MBT – Ecodeco with onsite MRF	60ktpa	1.5ha
MBT – Ecodeco with onsite EfW	180ktpa	4.2ha

- Maintenance Costs – Maintenance costs are identified for the lifetime of the technology. For example maintenance costs of 30ktpa Plastic (optical separation) diversification technology are estimated at £30,000 every 3 years, with a major overhaul of technology costing £100,000 at 9 years (King, 2003). These costs are converted into £ p t giving values of £0.34 pt for years 1 to 8 and £3.34 pt in year 9.

- Planning Costs - Planning costs were identified at £250,000 per project on average based upon data received from Shanks Waste Group (Lowe, 2002) though they can vary significantly depending on the size of the project and opposition to planning. These cost are converted into £ p t depending on the size of the new technology to be developed. Uncertainties to costs are modelled by applying fixed, non-linear and random variation to costs variables.

- External Costs – The external costs are the costs associated with technologies to reflect their environmental and social impact. They include Environmental Costs, Disamenity Costs and Avoided Burden Costs.

  - ♦ The environmental costs of different processes are identified through quantitative measurements of the emissions of a technology. These emissions are multiplied by a unit damage cost estimate to identify the total environmental cost. These costs are derived from Eunomia (Hogg, 2003). They identified key issues relating to their derivation:
    - ▪ The external cost is principally focused on air pollutants with emissions to other media treated on an individual process basis.
    - ▪ The environmental impacts of plant construction have not been considered.
    - ▪ The use of unit damage costs effectively assumes that impacts are invariant to the source of emission. In reality, population density and height from which emission is discharged will affect costs.

  The degradation of the putrescible waste material within a waste management system is an issue to consider, as rubbish is more difficult to sort the longer it is stored. If rubbish is allowed to decay in storage issues of health and safety, waste composition and value of material need to be considered. To reflect this, an additional environmental cost is added when calculating overall costs. The size of the additional environmental cost is calculated as equal to the environmental cost of storing waste at a compost facility. This cost is intended to reflect the additional consequences of having to deal with the degrading material. The waste flow is fractionated with flows leading to nowhere to reflect the decrease in volume of waste material.

- Disamenity is the adverse impact on local community of living in the vicinity of a waste treatment technology. Calculation of disamenity costs is in proportion to impact of house prices in the area, (see section 5.4.3, Table 5.4). The disamenity cost helps apply a social cost value to the performance of the waste management systems. Thereby addressing a limitation of waste management models identified in Chapter 2 i.e. the failure to account for economic, environmental and social impact of waste management systems.

- Avoided Burden costs are the net benefit of avoiding having to burn fossil fuels and the associated environmental damage if the energy can be produced through alternative based fuels e.g. Energy from Waste.

The model calculates the net unit 'operating' cost associated with different waste strategy scenarios. The costing sub-models calculate the cost of transferring 1 unit of waste through the main sub-model. Net unit 'operating' cost is calculated by dividing the total cost of processing by the material flow through each sub-model.

For example, to calculate the total external costs of a New Technology (Ecodeco)

variable:External Costs per New Tech Site=NT_Environmental_Costs+NT_Avoided_Burdens_Costs+NT_Disamenity_Costs

where[NT_Environmental_Costs=New Technology Environmental Costs,NT_Avoided_Burdens_Costs=New Technology Avoided Burdens Costs,NT_Disamenity_Costs=New Technology Disamenity Costs]

To calculate the total costs per unit for the New Technology facility in £ per tonne

Cost=Transport_Costs_to_NT_Sites+Financial_Costs_per_Nt_Site+External_Costs_per_NT_Site

where[Transport_Costs_to_NT_Sites=Transport Costs to New Technology Sites,Financial_Costs_per_NT_Site=Financial Costs per New Tech Site,External_Costs_per_NT_Site=External Costs per New Tech Site]

To calculate the overall Net Unit Cost in £ p t of processing 1 tonne of waste through the new technology (Ecodeco) facility

> *variable:Overall Unit Cost of New Technology=Total_Cost_of_New_Technology_Scenarios/(New_Teched+1)*
>
> *where[New_Teched=Totalwaste inventory at the new technology,Total_Cost_of_New_Technology_Scenarios=Total Cost of New Technology Scenarios]*

(Simile doesn't operate if dividing equations ever suggest 0, therefore whenever using divide signs in an equation the dividing quantity is +1. This fails to make any significant impact on the results given that the quantities of materials being processed are in the thousands of tonnes.)

5.3.6 Defining the network

The defining of the network and the flows between process technologies are constrained by the design of the waste management system in the UK. The path or flow of waste is constrained by operational constraints e.g. the fragmentation of the waste management system in the UK between waste collection and waste disposal authorities. Waste flow is constrained by legislation e.g. the need to pre-treat all waste prior to landfill disposal as identified in the Landfill directive. Waste flow is constrained by the characteristics of technology e.g. to meet the waste hierarchy of preferred technology energy from waste technology follows a pre-treatment recycling or recovery technology such as source separation schemes.

In defining the network and flows within the model these constraints of the system should be modelled to simulate the complicated system. But through simulating these constraints opportunity for new technology might be lost.

The model reflects a trade-off between the ability to simulate the waste management system and opportunity for technology through innovative thinking. The modelled flows are a simplification of the system to enable variation to the timing of technology change and the aggregation of new technology.

The flows (numbered) between sub-models or processes are identified in Figure 5.3 and described below:

Waste Generation and Collection Processes – Flows 1, 2 and 3 all identify the flows between the waste collection schemes and a decision sub-model to transfer the collected waste to a further processing technology. As described in Chapter 4 the collection of waste can be through various bulk or source separation schemes.

> Flow 1 - Waste Collection from Households, which is the waste collected by bulk, blue box and orange bag schemes feeds into a total waste collection for the region.
> Flow 2 - Bring Site waste, which is the waste collected by bottle banks etc adds to the total waste collected.

Flow 3 - HWRC (Civic Amenity) waste collection is the bulky waste delivered to civic amenity sites flows into the total waste collection.

The waste is aggregated into either unsorted bulk waste or sorted source separated waste. The generated and collected waste is transferred into the two decision sub-models. Waste Transfer Flows 4, 5 and 6 show the technology options available after the collection of waste is completed. The divergence of waste into sorted and unsorted categories allows the model to be used to investigate the cost of the waste technology needed to achieve the various targets defined in waste legislation, as identified in Chapter 1. Any recycling and recovery of the unsorted fraction, accounts for an improvement in the treatment/recycling performance.

Flow 4 - Waste that is not sorted i.e. unsuitable for recycling goes to a decision sub-model from which waste can be transferred to a suitable processing technology i.e. EfW, MBT or Landfill.
Flow 5 - The sorted collected waste is transferred to the Materials Recovery Facility. Here the resource is 'packaged' or diversified to improve potential for market value.
Flow 6 - Sorted green fraction of collected waste is transferred directly to the Composting facilities in the region.

After processing by the MRF technology the waste is transferred to further treatment technologies. Flows 7, 8 and 9 show transfer of waste from the MRF to a secondary processing stage. The recovered material that is transferred to recycling reprocessing facilities or markets is lost to the network.

Flow 7 - Shows the transfer of material from the MRF that is unsorted and could be used for secondary processing.
Flow 8 - Shows the transfer of rejected material from the MRF suitable for disposal to landfill.
Flow 9 - Shows the flow from the Material Recovery Facility to landfill.

Flows 11, 12, and 13 - Show the transfer of the unsorted bulk material to a secondary technology for processing 11 goes to EFW, 12 to Mechanical Treatment Technology, 13 to Landfill.

Flow 10 - Shows the flow from the Composting facility to landfill.
Flow 15 - Shows the flow from EfW to Landfill

Flow 16 - Shows the transfer from MBT to landfill, MBT produces RDF which then needs incineration. If incineration is on-site then it is transferred to the EfW via Flow 14. If there is no incineration available on-site it is exported to Dundee.

Other key issues in defining the model network:

- How does the model allow variation to the timing of technology change? Through the use of timing variables throughout the model, the timing of technology change can be displayed through turning flows on or off between technologies.

For example to divert 25% of collected unsorted bulk waste from Landfill to an Energy from Waste facility at 'time period' 310 weeks.

variable Landfill diversion: if strategy_time>310.1 then 0.75 else 1

where[Strategy_time= time in weeks from 2000]

variable efw diversion: if strategy_time>310.1 then 0.25 else 0

where[Strategy_time= time in weeks]

- How does the model allow variation to the aggregation between different types of technology? Given the model design and the timing variables the decision sub-models can be used to aggregate technology.

For example, the flow 'Refuse Derived Fuel Pellets' resulting from the Ecodeco process is transferred to an Energy from Waste Facility either in or outside of the Bedfordshire sub-region via Flow 14 depending on the availability of technology in the Bedfordshire sub-region.

For example, if exporting RDF Pellets within Bedfordshire then 1 else if export outside of Bedfordshire sub-region then 0

variable:RDF Export Decision Destination=0)

where[RDF_Export_Decision Destination=RDF Export Decision]

flow:RDF Export to Beds EFW Plant=(if EFW_Export_Decision_Destination==1 then RDF_Pellet_EFW_INVENTORY else 0)

where[RDF_Pellet_EFW_INVENTORY=RDF Pellet EFW INVENTORY,EFW_Export_Decision_Destination=RDF Export Decision Destination]

flow:RDF Export to Outside Beds EFW Plant=(if EFW_Export_Decision_Destination==0 then RDF_Pellet_EFW_INVENTORY else 0)

where[RDF_Pellet_EFW_INVENTORY=RDF Pellet EFW INVENTORY,EFW_Export_Decision_Destination=RDF Export Decision Destination]

Other aggregation of technology can be modelled by simply applying two or more technology changes to a single scenario. For example to model 2*60ktpa Ecodeco facilities operational by 2005 then a further 4*60ktpa Ecodeco facilities at 2010. The processing rates, storage capacities and costs etc are all timed to change at 2005 and 2010 respectively.

- How does the model allow variation to the aggregation of technology scale/capacity? Through varying the capacity of facilities to be modelled and the respective processing, storage, transport distances and costs associated with the technology and scenario. For example assessing variation between 2*200ktpa EFW facility and a single 400ktpa facility.

  variable:EfW Processing Rate=7692
  The weekly EFW processing rate in tonnes per week for either a 2*200ktpa or a 400ktpa EFW facility will not vary.

  variable:EFW Storage Capcity=(if EFW_Storage_Capacity>33334 then 0 else 1)

  where[EFW_Storage_Capacity=EFW Storage Capacity]

Storage capacity at the EFW facility will be the same for a 2*200ktpa technology or a single 400ktpa facility.

variable:EFW Operating Cost=28.2

Operating Cost will vary as different scales of facility operate at different costs. The 2*200ktpa operating cost is £28.20 per tonne, for a single 400ktpa facility the operating cost is reduced to £24 pt.

The transport distance will vary between the two technology scenarios as the location of a single facility in a region is different to two smaller facilities serving one-half each of the region. Transport distances to the EfW facility is reflected in the Unsorted Waste Transfer sub-model and calculated as described earlier in the chapter.

5.4 Model data management

With greater knowledge, understanding and accuracy of the operational data within the waste management system decisions on system performance and opportunity for new technology are improved. The difficulty is that in the UK waste industry the availability and accuracy of this data is poor.

5.4.1 Data acquisition

In attempting to acquire the data for the model, flaws in UK waste data collection and recording techniques were exposed (Environment Agency R&D Technical Reports P240, 1999 & P347, 2000). As identified in Chapter 1, section 1.2, a weakness of waste policy is the lack of clarification of waste definition. Criticism of waste data includes the lack of standardisation to waste auditing. This is created by the varying definitions of waste, the varying waste sampling techniques and the multitude of different classification methods employed. In conducting waste audits the perspective of the auditor can influence the audit process adding bias to waste data. For example in the waste industry local authorities and waste companies will often use the ambiguity of waste classification and auditing techniques to enhance their strategy performance figures relating to recycling etc. Authorities do not want to appear to be less efficient or productive in attaining targets.

The lack of data on waste generation and composition is reflected by a number of recent projects on the subject to standardise information. For example:

- the Biffaward Mass Balance UK (ETSU, 2001);
- the Institute of Waste Management Dataflow Project - The development of a national municipal wastes database (CIWM, 2002);
- the Environment Agency's Strategic Waste Management Assessments 2000 (Environment Agency, 2001).

An advantage of selecting the Bedfordshire sub-region as the case study was the availability of data identified for the UK Environment Agency 'WISARD' assessment of Bedfordshire waste strategy as highlighted earlier in the chapter.

5.4.2 Data Variability

The range of some variables within the model can be very large. For example as identified in Chapter 2, Table 2.1, the market price for recycled paper varies significantly over a short time period of only 3 years. With over 100 variables within the model it is not possible to model every range of high and low values for each variable thus average values are often used within the model. Determining which variables to adopt average values and which to alter depends on the objectives of the model scenarios to be assessed.

5.4.3 Data Gaps

There are various holes in the data e.g. Environmental Externality data for emerging or unproven technology. By modelling technology that is operational in other parts of the world but not in the UK e.g. Energy from Waste 'Pyrolysis' and Mechanical Biological Treatment 'Ecodeco' technology this is less of a problem. These data gaps are filled according to the scenarios to model though there is not a single rule to identify data gaps. Simple cross calculation work is used to derive an idea of some of the missing data. For example in the allocating of Disamenity costs for MBT Ecodeco technology. The Disamenity cost of a Composting facility, an Energy from Waste facility and Landfill facility are used as guidelines to identify a comparable value for an MBT technology. The Disamenity cost of an MBT process is assumed to be the same as a landfill when no onsite incineration occurs and the same as an EfW with onsite incineration. This is based upon the assumption that the MBT facility is comparable to a landfill facility in terms of the scale of transportation in/out of the facility. If an EfW facility is built onsite as part of the process it is perceived to have a higher health risk from the local community, therefore it adopts the higher Disamenity cost associated with an EfW facility.

Table 5.2 - The Allocation of Disamenity Cost (in £ per tonne) to an Mechanical Biological Treatment facility adapted from Hogg, 2003

Technology	Composting	MBT	EFW	Landfill
Avoided Burden Cost	6.73	11.69 without onsite EfW of RDF and 33.5 with onsite EfW of RDF	33.5	11.69

5.4.4 Model Calibration

The model has been calibrated (to an extent) by setting up the model with 1998/9 mass balance data and 2003 costing data. Technology scenarios are modelled to compare the model output data for number of households, waste generation etc. at years 2005, 2010, 2015 and 2020 against other waste management data forecasts e.g. using the Environment Agency (2000) data. It is further calibrated by calculating that the flows inputted into the model equal the flows outputted. It is intended to further calibrate the model through a comparison with the Mouchel 'Puragmentum' model as a potential further work issue described in Chapter 10. Costs are varied significantly in the scenarios analysed to reflect uncertainty associated with costs.

5.4.5 Model Sensitivity – Risk versus Uncertainty

As identified in Chapter 4, section 4.2.4, in any technology assessment the ability to assess both for risk and uncertainty is important. With over 100 variables within the model determining which variables to test for sensitivity is achieved through a combination of existing knowledge and random noise modelling.

5.5 Results

The structure for calculating the cost profile of technology over time using the Simile model:

1. Identify the time period of assessment.
2. Input model with data for the Bedfordshire sub-region. From now on this is known as the Base Condition.
3. Run the model over the time period to identify net unit 'operating' costs.
4. Input model variables to simulate variation to technology and system design.
5. Run the model identifying net unit cost over the time period.
6. Calculate the discounted net unit cost.
7. Calculate the annual discounted unit cost.

The results are displayed in various graphical forms:

- Waste throughput versus Time. The waste throughput graphs are used to help determine the capacity of facilities required to maintain operational processing rates. Through working backwards the capacities of facilities needed to meet the throughput demands can be calculated. They are also used to determine recycling and recovery rates of waste materials. This allows assessment as to whether legislative targets for the future are achieved.

The model is run for a time period of 30 years from 2000 to 2030. This allows a potential technology operation time of 25 years from 2005, allowing a brief time period for planning and construction time of the technology. A time period of 25 years is generally the maximum that local authorities will currently tender contracts for waste management (Mitchell, 2003). The model supports strategy assessment for greater (unlimited) or shorter time periods and it allows for aggregation of technology within the time horizon.

- 'Real' Net Unit Cost versus Time in £ per tonne of MSW over the time period of the assessment i.e. from 2000 to 2030. The real cost is the cost of strategies without discounting.

- Discounted Net Unit 'Operating' Cost versus Cumulative throughput of unsorted or sorted waste with the time identified when the throughput will be attained given the fixed growth rate modelled. Cumulative throughput was identified as the assessment is to identify the impact on the wider integrated system, not just the impact on individual technology. Given the key impact on operating cost due to landfill capacity being exceeded (as will be displayed in the results in Chapters 7-9), cumulative throughput is more valuable than annual throughput. In the UK as landfill void space diminishes the practice of exporting waste between regions will become increasingly expensive. This is coupled with the legislative and regulatory demands for local waste authorities to handle waste within their local proximity. Thus the need to maintain landfill capacity for waste generated in its own region becomes a key importance in waste strategy.

The discount rate converts all costs and benefits to present values. The difficulty is that the discount rate will vary according to the perspective of the evaluation with higher discount rates to reflect higher returns and the risk associated with investment from a private waste company perspective.

The Discount Rate = the Social time preference rate + inflation

The 'Social Time Preference Rate' (STPR) is the rate at which society values present money (or 'cash in hand') compared to its potential future value. The UK government identifies a current STPR of 3.5% (HM Treasury, 2003). This is currently very low reflecting the low public interest rates in the UK, in the last two decades rates of 3-15% have been identified (Ross Westerfield Jordan, 2003).

Within the scenarios modelled the discount rate is varied to reflect both environment uncertainty and the perspective of the decision-making evaluating the technology performance.

- Annual Discounted Net Unit Cost to determine the annual costs of waste strategy. It is difficult to identify the timing and scale of payments for high capital cost technology as the payments will be phased and timed according to individual waste contracts and accounting techniques. Given the varying accounting techniques and uncertainty over the timing of capital investment in new technology two approaches to presenting annual costs are used. In Chapters 7 and 8 annual cost profiles display capital costs as investment at a single point in time, this is to display the scale of costs needed for waste technologies. In Chapter 9 an alternatively costing technique called the Annual Average Equivalent Value (AAEV) is used. This distributes the costs of the capital investment over the lifetime of the technology assessment. The two techniques and results are compared in Chapter 9 to assess the extent to which the costing technique can affect the results, the cost of policy compliance and the opportunity for new technology.

5.6 Summary

This chapter has described the design and development of the model in the Simile Process Simulation Modelling Software. The chapter has reviewed the practical considerations of designing a model to consider the economic, environmental, social and operational factors that influence an integrated waste management system. The chapter has identified trade-off between model design and the ability to simulate the complicated waste management system.

The model has been developed addressing the limitations of previous waste management models to consider these influences. The model is designed to allow investigation into the opportunity for new technology and the cost of compliance to waste policy.

Chapter 6 describes the selection of scenarios to model to provide a robust appraisal of the cost of compliance to EU waste policy and the extent to which policy is constraining the opportunity for new technology in the Bedfordshire sub-region of the UK.

Chapter Six – Scenario Options

6.1 Introduction

The model is not intended as a comprehensive formulator of strategy identifying optimal waste strategy solution. It is intended as an investigative tool to identify and evaluate technology performance over time enabling investigation of the cost of policy. The methodology for scenario modelling should have a degree of flexibility and fluidity in order to allow such investigative research to occur.

Through identifying the cost of developing new technology, an assessment as to the extent to which the pathway of opportunity for new technology is constrained by policy can be estimated.

This chapter identifies the scenarios to model given consideration of the economic, environmental, social and operational factors that have been identified to influence the opportunity for new technology in the Bedfordshire sub-region. The scenario options available to model are described in Table 6.1 below.

Table 6.1 – Matrix of technology options available within the model

Technology Performance	**Timing of technology Change**	**Aggregation of different technology types – technology options**	**Aggregation of scale/ capacity of technology and location – spatial resolutions**	**Environment Uncertainty – options modelled to reflect uncertainty**
Scenario Options	▪ Single phase ▪ Multiple phase	▪ Materials Recovery Facility with additional sorting ▪ Composting ▪ Energy from Waste ▪ Ecodeco with onsite incineration ▪ Ecodeco with offsite incineration ▪ Landfill	▪ Bedfordshire Sub-region ▪ East Anglia region	▪ Market prices for recycled materials ▪ Transport Costs ▪ Distance between facilities and markets ▪ Waste Composition ▪ Discount Rate ▪ Planning and maintenance cost ▪ Capital cost (subsidised)

6.2 Identifying a semi structure to the Modelling of Scenarios

To model every scenario option and combination within Table 6.1 would not be beneficial to understanding the opportunity for new technology. A semi structure to modelling scenarios is used to identify weaknesses in waste strategy created by the operational demands/constraints of process technology in the Bedfordshire sub-region. These weaknesses identify opportunities for needed technology change. The advantages of this investigative approach include:

i. It will save on time on the number of scenarios to run.
ii. It will assist in the analysis and understanding of results through progressive learning.
iii. It will allow identification of the key and most sensitive decision drivers/variables.
iv. It offers flexibility to represent localised conditions.

Disadvantages of this investigate approach include:

i. The confidence in any analysis is judged by the ability (and expertise) of the operator to select scenarios to model as a complete matrix of technology options is not modelled.

Through identifying limitations in the Bedfordshire's waste strategy over the next 30 years the need and opportunity for new technology can be identified. This can help reduce the scope of scenario modelling and provide insight into operational constraints/demands on technology that will affect the Bedfordshire sub-region over the next 30 years if current waste strategy and environment conditions are maintained. For example:

- Required versus available technology capacity over time to meet increasing waste generation.
- New technology needed to meet shifting environmental legislation requirements such as single stream targets, recycling targets, the need to pre-treat all waste prior to disposal etc.

6.3 Weakness in the current Bedfordshire sub-region waste strategy

The Bedfordshire sub-region within the modelling exercise is referred to as the 'Base Condition'. The base condition describes the current waste strategy in the Bedfordshire sub-region as described in Chapter 4. Modelling the base condition identifies the net unit cost of maintaining the current waste strategy for the Bedfordshire sub-region for the next 30 years. The results of maintaining the base condition set-up are described below.

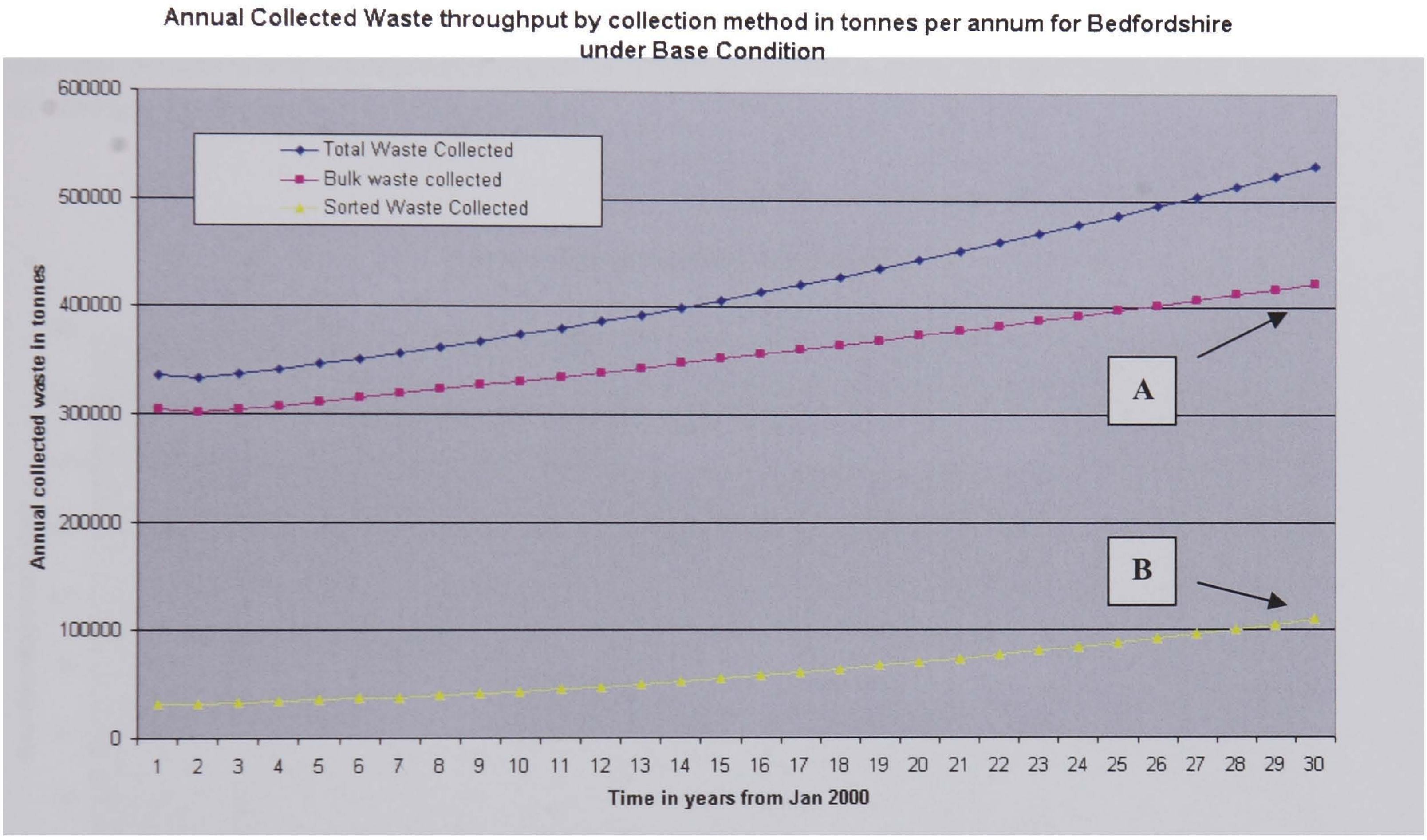


Figure 6.1 – Waste generation and throughput for the Bedfordshire sub-region

Table 6.2 - Waste Generation and Processing in the Bedfordshire sub-region

End of Year	**Annual Bulk Collected Waste in tpa**	**Annual Sorted Collected Waste in tpa**	**Weekly Bulk Collected Waste in tpw**	**Weekly Sorted Collected Waste in tpw**
2000	294,291	33,207	5,663	639
2010	332,620	43,759	6,397	842
2020	375,958	71,569	7,230	1,376
2030	424,983	111,384	8,173	2,142

Table 6.2 highlights the tonnage of waste collection at intervals in the Bedfordshire sub-region. Figure 6.1 and Table 6.2 help determined the size of treatment technologies to be modelled i.e. needed capacity to meet future waste generation.

- Point A – the maximum unsorted waste collection is approximately 420ktpa at 2030. This helps determine the maximum needed capacity of technology as the landfill directive requires all waste to be pre-treated prior to disposal to landfill as highlighted in Chapter 1.
- Point B – the maximum sorted collected waste is 102ktpa at 2030 if current collection and recycling rates are maintained.

In reality the recycling rate and collection rate will vary as the waste strategy needs to be changed to meet growing legislative targets as described in Chapter 1.

Figures 6.2 and 6.3 identify the net unit cost in £ p t for the Bedfordshire sub-region or Base condition. Figure 6.3 shows the discounted costs of the base condition. The current Social Time Preference Rate (STPR) of 3.5% is used to reflect the time value of money as discussed in Chapter 5.

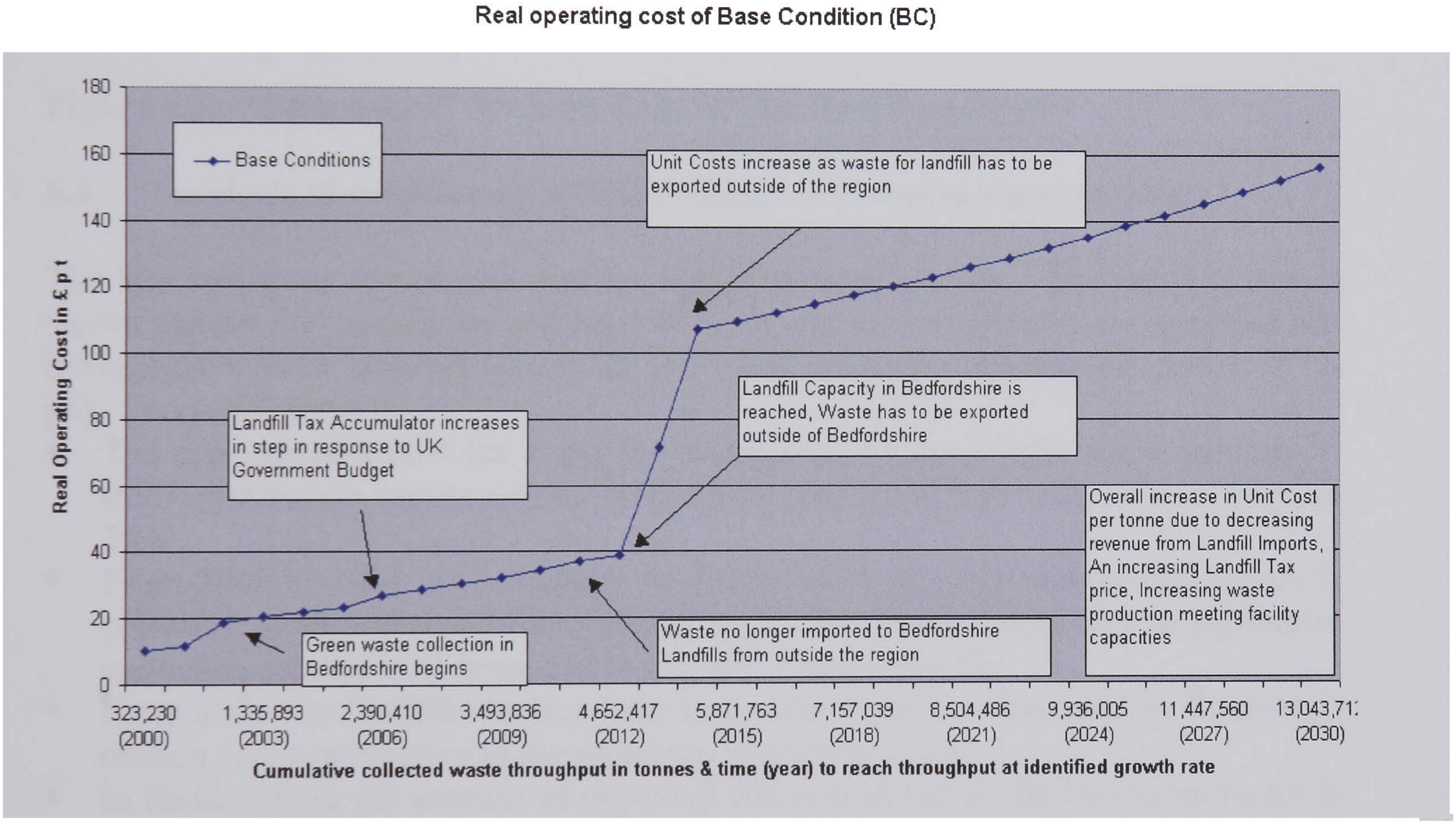


Figure 6.2 – 'Real' net unit cost for the Bedfordshire sub-region (base condition).

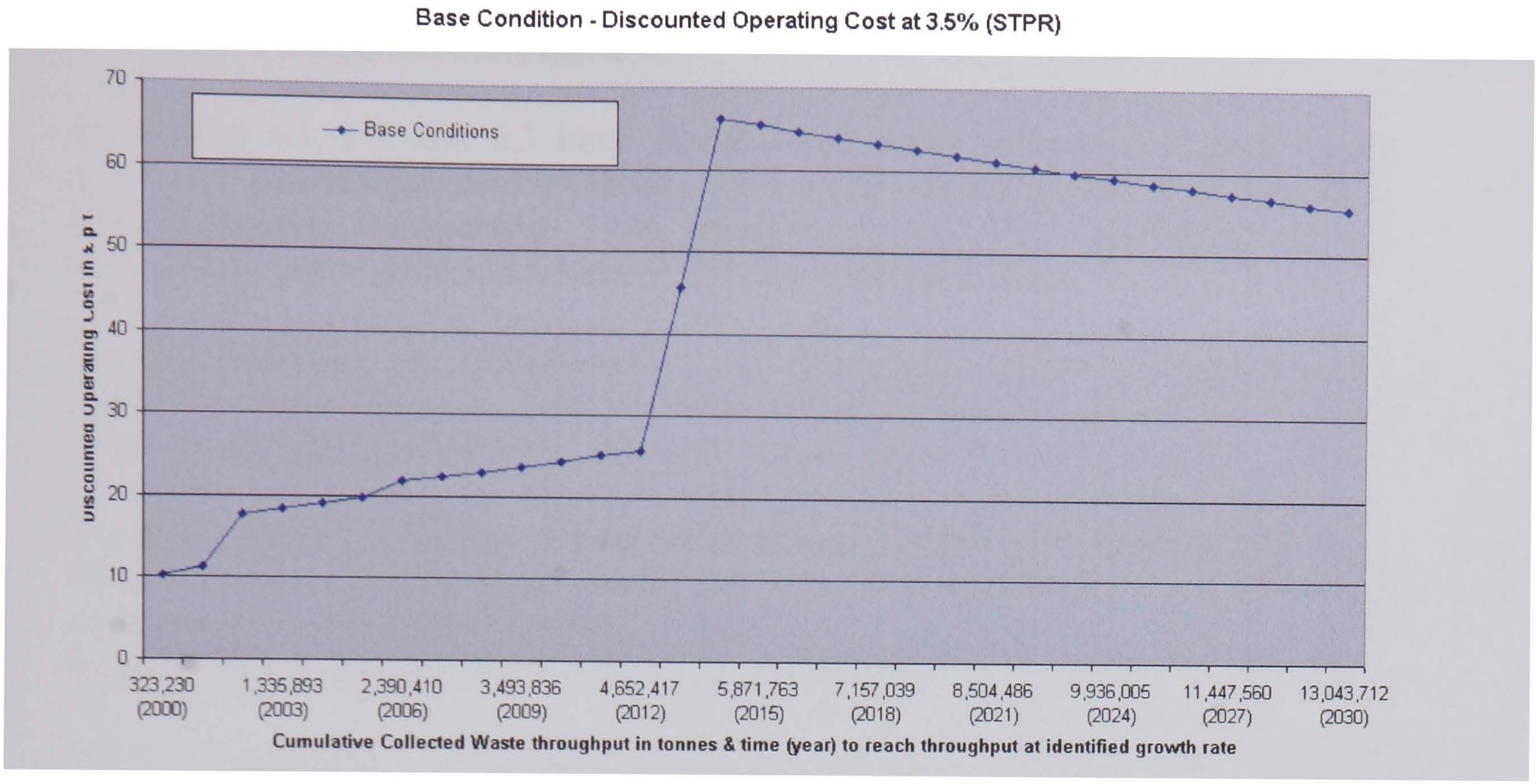


Figure 6.3 – 'Discounted' Net Unit Cost for the Base Condition

6.4 Analysis of weaknesses of Bedfordshire sub-region waste strategy

The key variations in net unit cost are identified and labelled. The net unit cost is shown against the cumulative collected waste throughput with the time (year) that this throughput will be attained (given the modelled waste growth rate of approx. 2.7% pa). Figure 6.2 shows:

- The real net unit cost (in £ pt) for assessment of the whole waste strategy in Bedfordshire sub-region ranges from approximately £10 pt in 2000 to £160 pt in 2030.
- From 2002 to 2004 costs increase as Green waste (kitchen and garden waste) is collected as an additional material stream for the Bedfordshire source separation collection schemes (as described in Chapter 4, section 4.2).
- From 2006 the landfill tax increases in greater steps (as described in Chapter 1, section 1.2) contributing to the increases in strategy costs.
- In Bedfordshire the amount of imported waste destined for Bedfordshire landfills is progressively being reduced. Under the waste strategy for Bedfordshire waste imported to landfill will be reduced by around 73tpw until 2010 when the amount of waste imported to Bedfordshire landfills will stabilise at around 500,000tpa (BCC, 2002). This reduction in the importing of waste to landfill affects the amount of revenue generated through the overall strategy. The overall strategy cost increases as revenue from imported waste decreases.
- The sharp variation at 2012 from approximately £40 pt to £110 pt (real cost) identifies the point where landfill capacity in Bedfordshire is exceeded. Costs increase dramatically as waste intended for landfill has to be exported outside of Bedfordshire.
- From 2015 the discounted cost in Figure 6.3 (i.e. costs at 2003 values) decrease compared to the increasing real cost in Figure 6.2. This is caused by the discount

rate of 3.5% being greater than the annual percentage growth in real costs. Before 2015 the annual percentage increase in costs is greater than the discount rate and therefore discounted costs increase.

As Figures 6.1, 6.2 and 6.3 have shown when waste collection or input into a technology exceeds processing capacity, changes to the cost profile occur e.g. when landfill capacity is exceeded. The capacities of the other operational process technologies in the Bedfordshire sub-region are discussed below:

Waste Collection – the model assumes that there is no maximum capacity on the tonnage of waste collected. This is as all waste has to be collected as a responsibility of the waste collection authority and costs are calculated as a function of the number of households in a region. It is not the objective of the thesis to investigate the relationship between variation to waste collection method and strategy performance. This is an area where the model could be developed in the future through calculating collection costs in relation to the number of collection vehicles, the collection transport routes, distance and the timing of collections etc.

Waste Composting – given that 'Green' or compostable waste collection in the Bedfordshire sub-region is only being introduced at the time of model development, as described in Chapter 4, the quantities of Green waste collected and processed by Bedfordshire's composting facilities is relatively small. In the Bedfordshire sub-region in 2000, 3783tpa of compostable 'Green' waste collected was processed by composting facilities with a maximum capacity of 40ktpa (Bedforshire County Council, 2002). The available capacity is sufficient to meet future compost facility demands if collection of 'Green' waste continues at the current rate. 'Waste Strategy 2000' (Defra, 2000a) sets increasing targets for the recycling and composting of household waste in the UK. As described in Chapter 1, by 2006 25% household waste should be recycled or composted and by 2015 this should reach 33%. The collection of 'Green' waste from households was introduced in 2003 in limited areas within the Bedfordshire sub-region and the waste strategy plan is to gradually expand this collection of 'Green' waste across the whole of the sub-region to assist in achieving these statutory targets (Recycling World, 2003). The composting technology capacity will need to be expanded when collection of 'Green' waste becomes more widespread. This is modelled and discussed further in Chapter 7.

Materials Recovery Facility – The waste strategy in the Bedfordshire sub-region is designed with all household collected waste transferred to the Materials Recovery Facilities where waste can be sorted, diversified and bulked before transfer either to a reprocessing facility or landfill for disposal, as described in Chapter 3. The maximum capacity of the Materials Recovery Facilities in the Bedfordshire sub-region is difficult to identify and justify as in reality the capacity is not just restricted by a single operational processing rate (Bedfordshire County Council, 2002). It is estimated that the current level of the Material Recovery Facility capacity is 60ktpa. Other factors such as local waste policy, available storage space, recycled material market prices, contracts between the MRF operators and the material reprocessing facilities all influence the operation of the MRF (Howard, 2002).

The model is designed to reflect restrictions on the maximum capacity of individual waste materials. This is as when capacity of one waste material is exceeded further capacity can be gained through not sorting other waste materials e.g. to gain additional capacity for Paper recycling, Plastic recycling is no longer sorted. Further investigation into waste material diversification at the MRF is modelled in Chapter 7. This is increasingly significant given the proposed EU waste policy shift towards material target setting as identified in Chapter 1, section 1.1. Figure 6.4 below shows the results of modelling a single maximum capacity and processing rate to the MRF technology in the Bedfordshire sub-region.

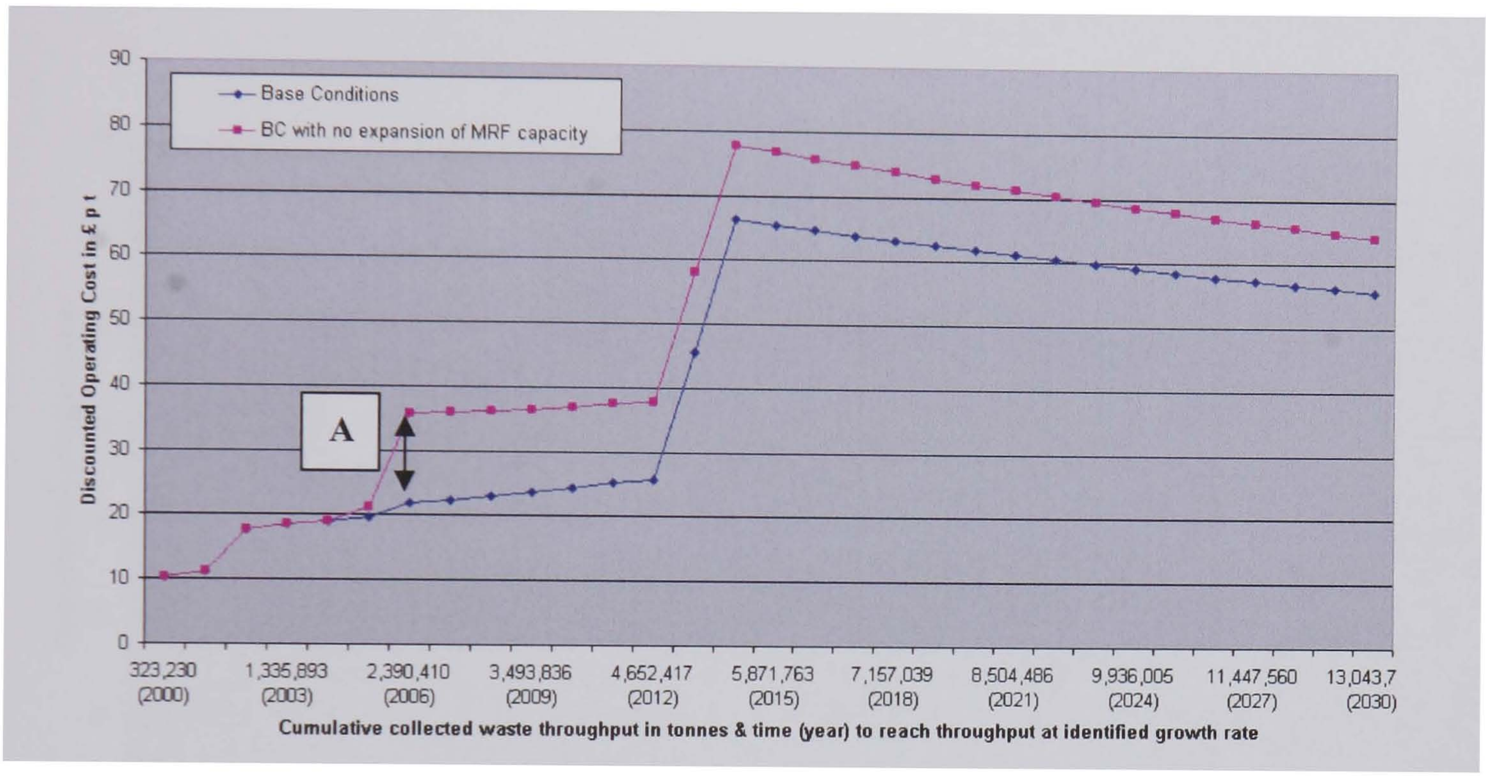


Figure 6.4 – Discounted operating cost through variation to MRF technology capacity at 3.5% discount rate

Figure 6.4 shows:

- Point A - if a single maximum capacity of 60ktpa is applied to the MRF, the model anticipates the MRF capacity to be exceeded in 2006 i.e. after 310 weeks. This occurs as the bulk waste is processed by the MRF not just the recycled waste materials. At this point operating costs increase from £21 pt to £36 pt at 2003 values as waste is transferred and stored at the MRF prior to disposal at landfill.

This conclusion that MRF capacity will be exceeded by 2006 is questionable as in reality extra capacity at the MRF is continually being created through changes to operational practice and site redevelopment allowing the MRF capacity to be gradually expanded to meet the growing waste collection rates (Howard, 2002). It is difficult to apply capital costs for this redevelopment or operational change as some of the costs are already 'sunk'. For example the land area, weighing bridge, planning permission etc can be already established as part of the original site/facility plans.

The key difficulty regarding available capacity at the MRF in the Bedfordshire sub-region is primarily created if additional waste streams or increases in recovery rates of materials occur. These will have to occur to meet the growing legislative targets as described in Chapter 1, Table 1.1. The MRF capacity is assumed to be continually regenerated with the potential reaching of capacity at 2006 selected as an initial time of when technology change is needed. By introducing alternative technology options at this time point the expansion of the MRF might not be needed.

Landfill – As identified earlier the most significant event in the base condition graph is when landfill capacity is exceeded at 2012. But like the MRF, in reality landfill space is continually being regenerated (Lowe, 2003). When modelling unlimited landfill capacity the capital cost of a 200ktpa landfill site is estimated to be £4m, though this can vary considerably depending on land value in the location of the landfill site (CIWM, 2003). Figure 6.5 compares infinite landfill capacity with finite capacity as determined by existing landfill resources.

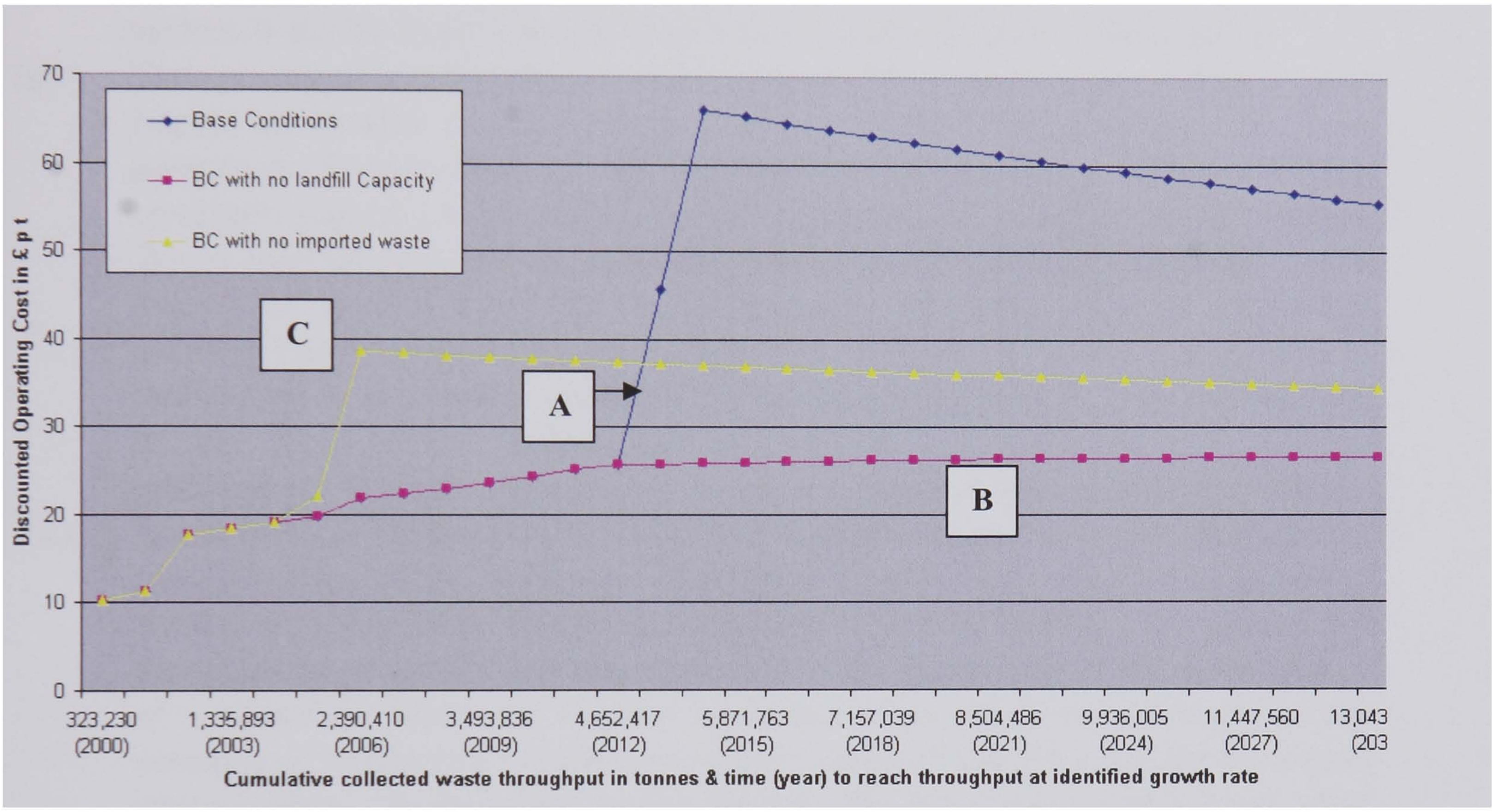


Figure 6.5 – Discounted operating cost at 3.5% for technology variation through infinite landfill capacity and no waste imports to Bedfordshire Landfill

Figure 6.5 shows:

- Point A - The dramatic rise in costs at 2012 when landfill capacity is reached compare to no landfill capacity from £26 pt to £66 pt at 2003 values (discounted cost at 3.5% discount rate).
- Point B - With no landfill capacity being exceeded much lower costs are realised, maximum £26 pt compared to £66 pt with finite landfill capacity.
- Point C – Imported waste is a key consideration of the system as around 60ktpw of waste is imported to Bedfordshire's landfill compared to only around 6ktpw waste generated in the region. The importing of waste to Bedfordshire landfill is planned to be gradually reduced from 2006 by around 73tpw (BCC, 2002). Point C identifies the impact of stopping this import of waste completely at 2006. It marks an increase in costs i.e. £21 pt compared to £39 pt (at 2003 values using a discount rate of 3.5%) as without imports revenue to the system is lost.

6.5 Summary of the Base Condition Results

Figures 6.1 to 6.5 representing the base condition help determine operational weaknesses in the current waste strategy for the Bedfordshire sub-region.

(i) The dependence on landfill in the Bedfordshire sub-region – the lack of alternative technology options within the current waste strategy is evident. The Landfill Directive requires the pre-treatment of all waste prior to landfill and the attaining of recycling and recovery targets as described in Chapter 1. Within the Bedfordshire sub-region the lack of waste process technology options such as Mechanical Biological Treatment and Energy from Waste that could help attain these legislative requirements is evident. Scenarios to assess technology options should include the introduction of such technology into the system if the Bedfordshire sub-region is to meet legislative requirements.

(ii) Transportation and transfer of waste between local authority boundaries - The impact of landfill capacity being exceeded at 2012 is primarily due to the quantities of waste imported to Bedfordshire landfills from outside the base condition region i.e. across the waste management boundary of the system. When landfill capacity is exceeded the cost increases dramatically. The impact of spatial resolution on opportunity for technology in the waste industry has been highlighted in Chapter 4, section 4.2.5, as a barrier to new technology in the waste industry. The base condition graphs show the reliance in the Bedfordshire sub-region for revenue to subsidise the strategy performance from the importation of waste to landfill from outside the region.

(iii) The impact of integration between technologies on technology performance - Simplification of the system and failure to simulate the influence of imported waste into the system would have resulted in biased results. For example if the technology assessment was restricted to the evaluation of the performance of a Materials Recovery Facility in terms of its efficiency to operate, any assessment would fail to reflect the significance of landfill capacity on overall strategy cost. Technology change through the development of a MRF plant might prove favourable in such an assessment but in the context of the wider system it is of minor significance.

(iv) The timing of technology change – Figures 6.1 to 6.5 have identified when the available processing capacity of technology in the Bedfordshire sub-region will be exceeded. Two timings of exceeding technology capacity are identified:

- Time (i) at 2006 when MRF capacity will be exceeded if MRF operation is not continually redeveloped. This timing matches the statutory target of 25% recycling and composting by 2006 as identified by the 'Waste Strategy 2000' (Defra, 2000a).
- Time (ii) at 2012 when landfill capacity is exceeded if strategy to continue the importing of waste to Bedfordshire's landfills is continued.

Other timing of needed technology change can be identified from the need to meet legislative targets or requirements as identified in Chapter 1. Other statutory targets for the UK as identified by the Waste Strategy 2000 that might be used to identified timings of technology change include 33% household recycling and recovery by 2015 (Defra, 2000a).

(v) The Annual Cost of Waste Strategy – Figures 6.6 and 6.7 identify the Real and Discounted net annual cost (at 2003 values using a 3.5% discount rate) of waste strategy respectively if the current waste strategy in the Bedfordshire sub-region is maintained up to 2030. Figure 6.7 shows that in 2003 the net annual cost is approximately £6.1m (note this is the 'net' cost not the total cost). When landfill capacity is exceeded between 2012 and 2014 cost rises to approximately £21.5m (at 2003 values). In Figure 6.6 the net annual cost continues to rise as waste generation in the Bedfordshire sub-region increases. In Figure 6.7 the net annual cost decrease after 2014 (as identified above this is due to the percentage annual growth in net unit cost being less than the discount rate). The costs show that waste management costs in the Bedfordshire sub-region whether real or discounted to 2003 values are going to increase significantly between 3 to 5 times 2003 values. When evaluating the cost of policy through modelling different waste strategy scenarios in Chapters 7 and 8 a calculation of cost can be derived by comparing the cost to these base condition costs.

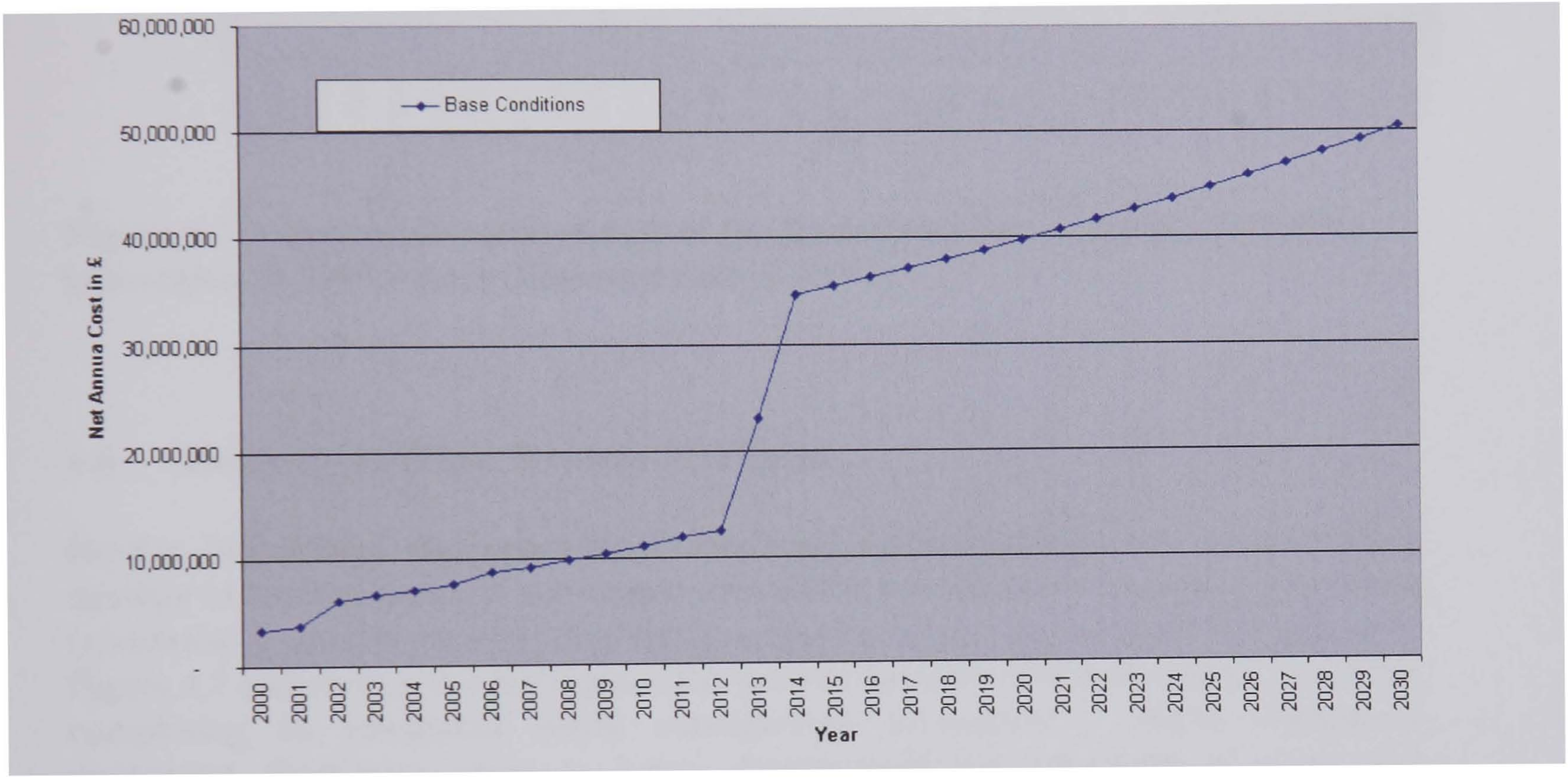


Figure 6.6 – Annual Real Cost of the Base Condition in the Bedfordshire Sub-region

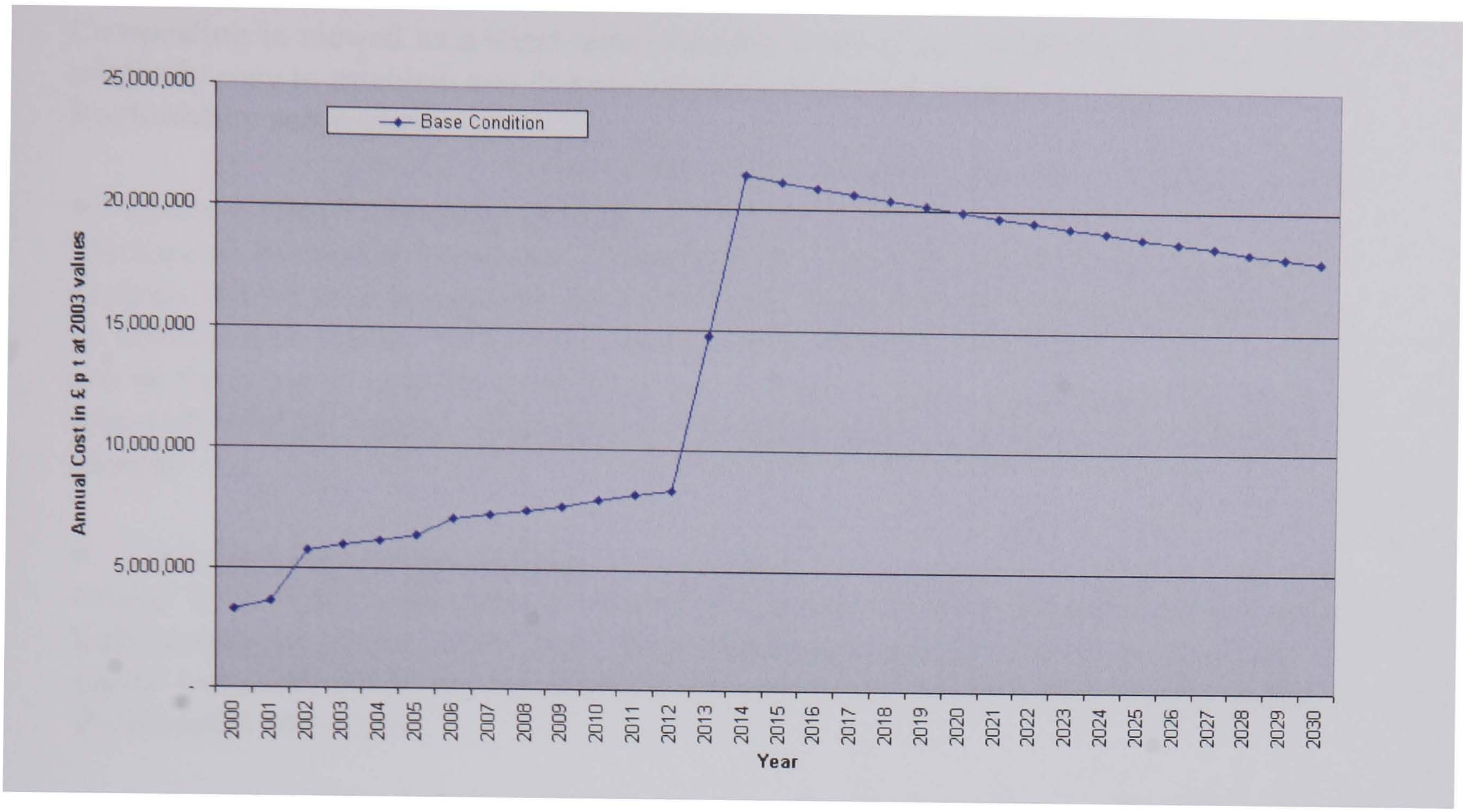


Figure 6.7 – Annual discounted cost of the Base Condition in the Bedfordshire sub-region at 2003 values (Discount rate of 3.5%)

6.6 Response to Waste Strategy Weakness

Having highlighted the operational weakness of maintaining the current waste strategy in the Bedfordshire sub-region identifying potential new technology solutions (scenarios) to model are identified using a varying time frame assessment approach. Figure 4.1 and section 4.1 highlighted the need to consider different time frames when completing an integrated waste management assessment. Waste companies implement short-term plans to waste management but long-term planning and adaptive technology strategies support sustainable development. By applying a classification to the technology options i.e. whether they are short, medium or long-term planning options a semi-structure to the scenario modelling can be achieved. The classification of technology planning into short, medium and long term technologies reflects an operational process constraint of technology options. For example short-term planning technology can be implemented at lower cost and in a short time period. (They reflect issues of the process of innovation as identified in Chapter 1, i.e. the timing and rate of technology change). Long-term technologies require a larger capital investment, a longer planning period and require dramatic change to current waste strategy.

- Short-term Technology Options

Variation to the Materials Recovery Facility and diversification of waste streams is classed as a short-term option. This is as it can be easily implemented, at low cost and with little variation to the existing waste strategy.

Composting is viewed as a short-term planning strategy as composting facilities are relatively easy to establish and there is already established composting facilities in the Bedfordshire sub-region.

- Medium-term Technology Options

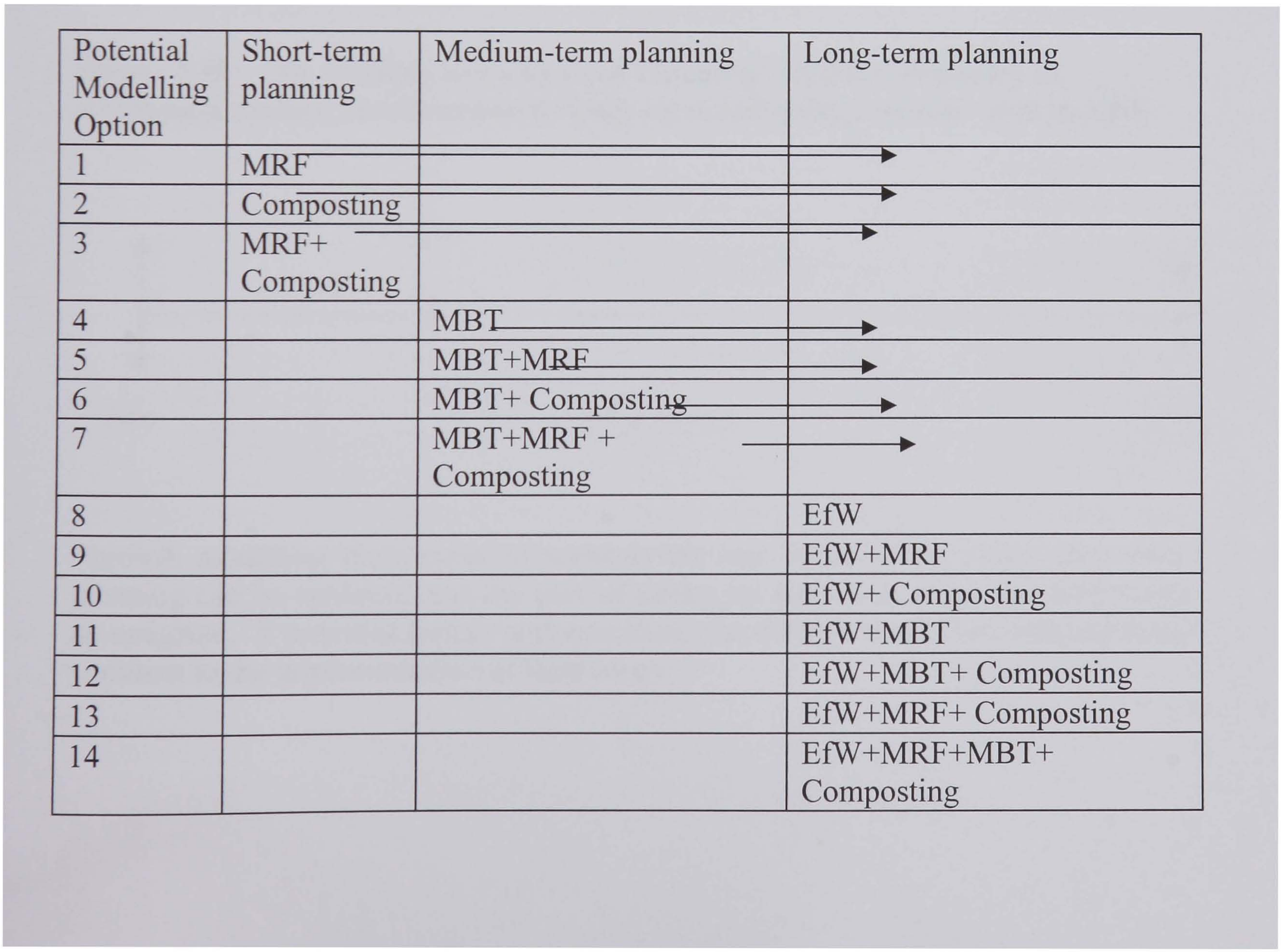
Mechanical Biological Treatment Technology is viewed as a medium term option as facilities can be built in modular units of 60ktpa. Therefore the scale of facilities can be controlled so that the technology can be implemented incrementally. Capital costs can be restricted to ease the technology into a waste strategy system and MBT treats unsorted recycled waste. Therefore the technology has a medium term planning process.

- Long-term Technology Options

Energy from Waste technology is viewed as long-term technology option as they are high capital investment technology. They require a long-term contract to recover the capital costs and would require dramatic changes to the current waste strategy in the Bedfordshire sub-region.

Having categorised the technology options into short, medium and long-term technology options a matrix of scenarios to model is easier to identify. Therefore over the time horizon to be modelled and using these assumptions Table 6.4 identifies the matrix of technology options available to model.

Table 6.3 - Scenario options based upon Strategy Planning Time Scales



Potential Modelling Option	Short-term planning	Medium-term planning	Long-term planning
1	MRF	→	→
2	Composting	→	→
3	MRF+ Composting	→	→
4		MBT	→
5		MBT+MRF	→
6		MBT+ Composting	→
7		MBT+MRF + Composting	→
8			EfW
9			EfW+MRF
10			EfW+ Composting
11			EfW+MBT
12			EfW+MBT+ Composting
13			EfW+MRF+ Composting
14			EfW+MRF+MBT+ Composting

Converting these options into scenarios to model can be displayed through the use of time horizons.

Figure 6.8 An example of Short-term Planning - Multiple technology change through short-term technology options such as variation to MRF diversification

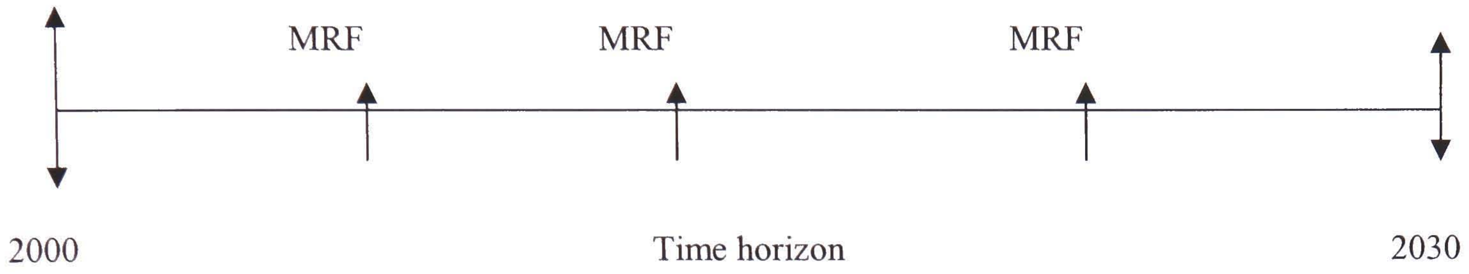


Figure 6.9 An example of Medium-term planning – multiple technology change through short and medium term technology options such as MRF diversification and MBT 'Ecodeco'.

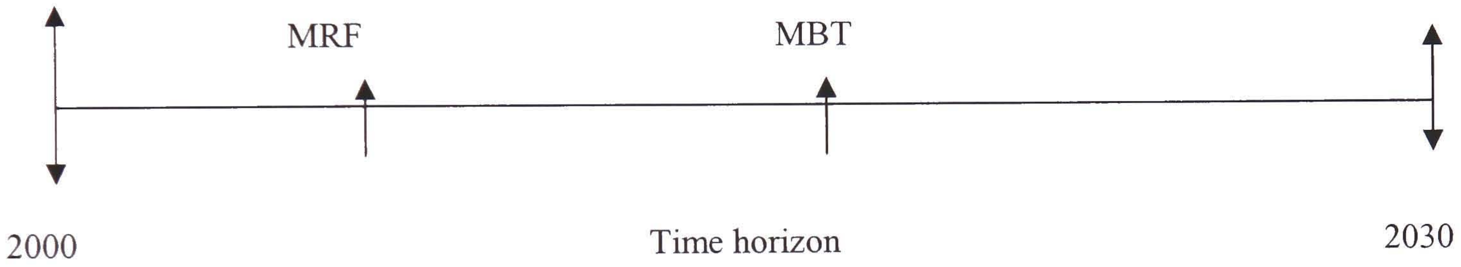
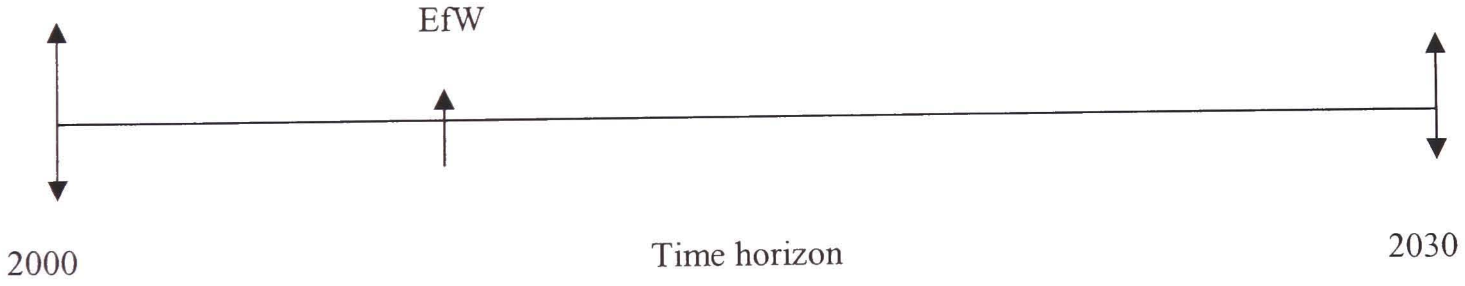


Figure 6.10 An example of Long-term Planning – reduce frequency of technology change to accommodate long-term technology options such as EfW



Through modelling these types of scenario the cost of long-term versus short-term planning can be achieved and the cost of policy on opportunity for new technology investigated. It provides further understanding into the process of innovation through variation to the implementation of technology.

6.7 Summary

This chapter has identified a semi-structured approach to modelling new technology options. There are limitations in adopting this approach:

i. Not all scenario options are identified or assessed.
ii. What is created is a pyramid of preferred technology through selecting favoured technology options from cost profiles. To what extent would the assessment differ if technology assessment incorporated a different structure?
iii. This process does not offer much imagination or creative thinking into the development of technology scenarios and it limits the opportunity for innovative thinking in identifying technology options.

Given these limitations it is important to stress that this approach is not a regimented approach to modelling but a semi-structured approach to reduce the amount of analysis of options. Being a semi-structured approach there is still the opportunity to assess other technology scenario options through progressive learning and investigation of the model.

Chapters 7 and 8 present the model results and analysis.

Chapter Seven – Modelling Results

7.1 Introduction

The chapter investigates the extent to which the barriers created by conflict between the economic, environmental, social and operational factors influence the cost of compliance to EU waste policy and the opportunity for new technology. The results provide evidence to answer the research objectives identified in Chapter 1, i.e. identifying the extent to which consideration of EU waste policy, the process of innovation and the technology assessment technique impact the opportunity for technology innovation.

The results are presented using the semi structured approach to scenario modelling as identified in Chapter 6. The results are presented as follows:

- Short-term planning technology options.
- Medium-term planning technology options.
- Long-term planning technology options.

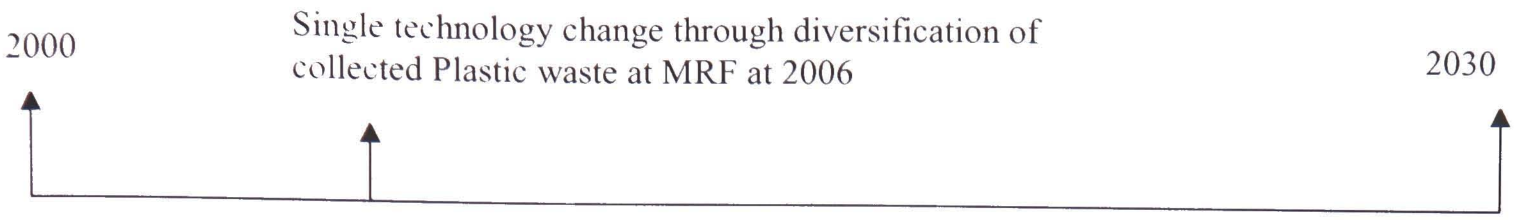
The scenarios modelled and presented are designed to investigate the cost of compliance to the 2006 and 2015 UK statutory targets for the recycling and recovery of municipal solid waste, as identified in Chapter 1.

7.2 Short-term Planning Options

7.2.1 Technology change through diversification at the MRF

Why use diversification of waste materials at the material recovery facility as a short-term planning technology option?

- UK waste planners and operators work primarily in short-term planning, reacting to the next target. In the waste industry the statutory target of recycling or composting of 25% of household waste by 2006 is the first target. Given that this is a statutory target the target is set for the whole of the UK and differs from Best Value targets that are assigned to individual authorities. The benefit of adopting the statutory target instead of the Best Value target is that sooner or later the statutory target will need to be reached by each authority.
- Technology change at a MRF through increased recycling by additional sorting and diversification offers an opportunity for incremental technology change, which is more likely to be implemented as identified in Chapter 1.
- It offers an opportunity to evaluate short-term planning technology option against long-term planning technology options (highlighted as a conflict of interest between private waste companies and socio-economic objectives in Table 2.2).



Scenario 7.1 – Time Horizon for technology change through diversification of Plastic waste stream at the MRF

The scenarios modelled reflect the opportunity for diversification of the plastic waste material at a MRF. This is through the development of a 10ktpa plastic sorting technology at an estimated capital cost of £600,000. It takes 6 months to install and develop such technology from planning and design with up to 15% of plastic waste rejected by the diversification technology (King, 2003). Revenue from Plastic waste diversification varies according to the market price for plastic i.e. HDPE, Clear PET, Coloured PET, Mixed Plastic. The timing of the technology change is varied to assess the impact of the timing of technology change on system performance. The initial technology change is modelled to occur at 2006 as this was identified in Chapter 6 as the first timing of needed technology change. Planning costs are assumed to be zero as the technology operates within the existing MRF infrastructure. To adopt the technology MRF unit cost (operating and maintenance cost) for the management of the Plastic waste material, change from £10pt to £62 pt of plastic (IWM, 2000).

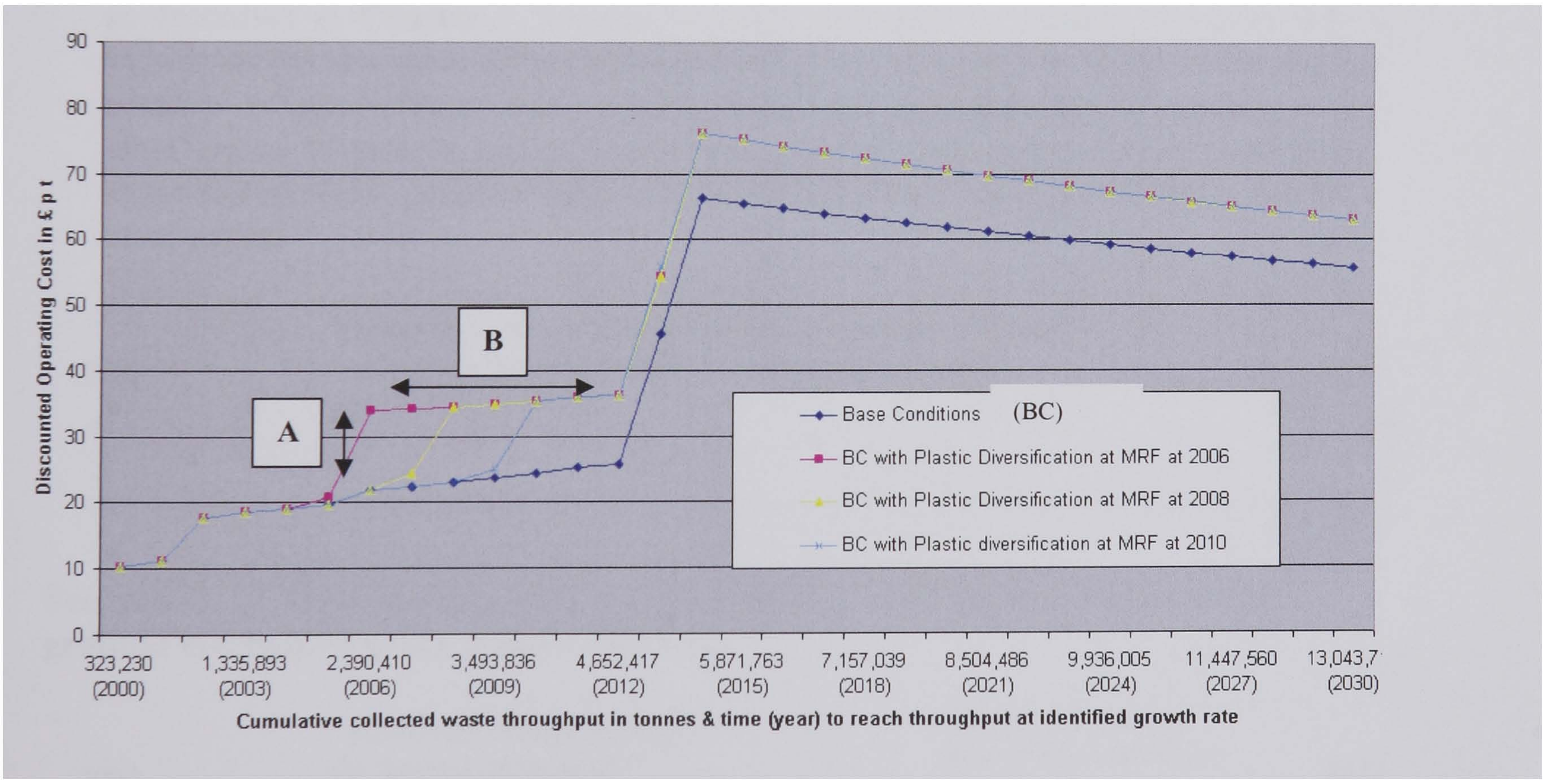


Figure 7.1 – Technology change through the diversification of the Plastic waste stream at the MRF net unit cost at 2003 values using a 3.5% discount rate.

Figure 7.1 shows:

- Point A - The discounted net unit cost for the Bedfordshire waste strategy increases from around £20 pt to £35 pt at 2003 values through the diversification of the plastic waste material. This differs from the increase in Plastic material operating cost i.e. £10 to £62 pt as identified above, as only a fraction of the waste stream is the plastic material and its impact on the system performance as a whole is minimal.

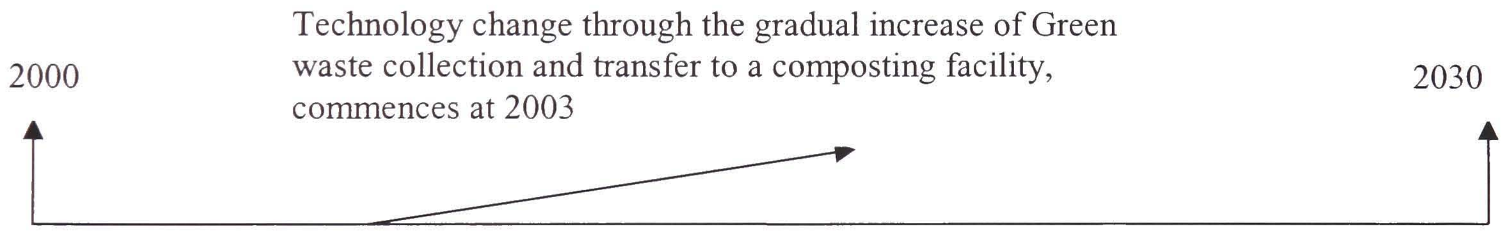
- Point B - Through varying the timing of the technology change from 2006 to 2008 and 2010 the net unit cost is similarly delayed. The delay in net unit cost or performance of the technology would be expected.

The results show variation from the Base condition identifying the cost of adopting the diversification of the plastic waste. Adopting this technology change would assist in progressing towards the 2006 statutory target of 25% recycling and composting of household waste. The maximum percentage of Plastic waste in the waste stream is only 7-8% as identified in Chapter 3, Table 3.1. Maximising the recycling of the plastic waste material would at best take the recycling rate in the Bedfordshire sub-region from 6-7% to 14-15%. The next scenario to assess includes the development of Composting facilities to compost 10% of household waste in the Bedfordshire sub-region to help achieve the 25% target.

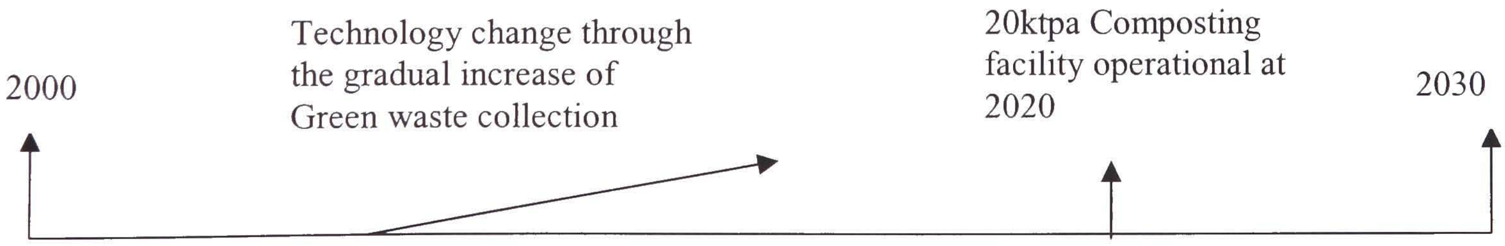
7.2.2 Technology change through the increase in Green waste Collection

Why model the increase in collection of green waste as a technology change?

- As described earlier, 'Green' waste collection in the Bedfordshire sub-region was gradually being introduced in 2003. Through modelling 'Green' waste collection across the whole of the Bedfordshire sub-region the timing of needed technology change through the expansion of composting facility capacity can be investigated.
- It offers the opportunity to investigate the cost of unfounded environmental policy as described in Chapter 1, section 1.2. For example the landfill directive sets targets for the diversion of biodegradable fractions of waste i.e. Green waste from landfill. 'Waste Strategy 2000' (Defra, 2000a) sets targets for the composting and recycling of household waste, as described earlier. Through modelling variation to the Green waste collection the cost of meeting these strategic objectives can be investigated.



Scenario 7.2 – Time horizon with single technology change event through the gradual increase of green waste collection



Scenario 7.3 – Time horizon with multiple technology change through the gradual increase of green waste collection and development of a composting facility.

The capital cost of a 20ktpa Composting facility is estimated at £500,000, the unit cost (operating and maintenance cost) for a 20ktpa composting facility is set at £26.40pt with compost sold to market at an average value of £7pt (Hogg, 2002, CIWM, 2003). The gradual increase in collection of green waste is achieved through modelling a linear increase in the amount of green waste collected as part of the total household waste collection from 2% in 2003 to 10% by 2006. The growth in Green waste collection is timed to assist in achieving the 2006 statutory recycling target for the recycling and composting of 33% of MSW as set out by the 'Waste Strategy 2000'. Collection costs rise by £10 pt to reflect the additional 'Green' waste collection. Planning costs are assumed to be £250,000 per composting facility.

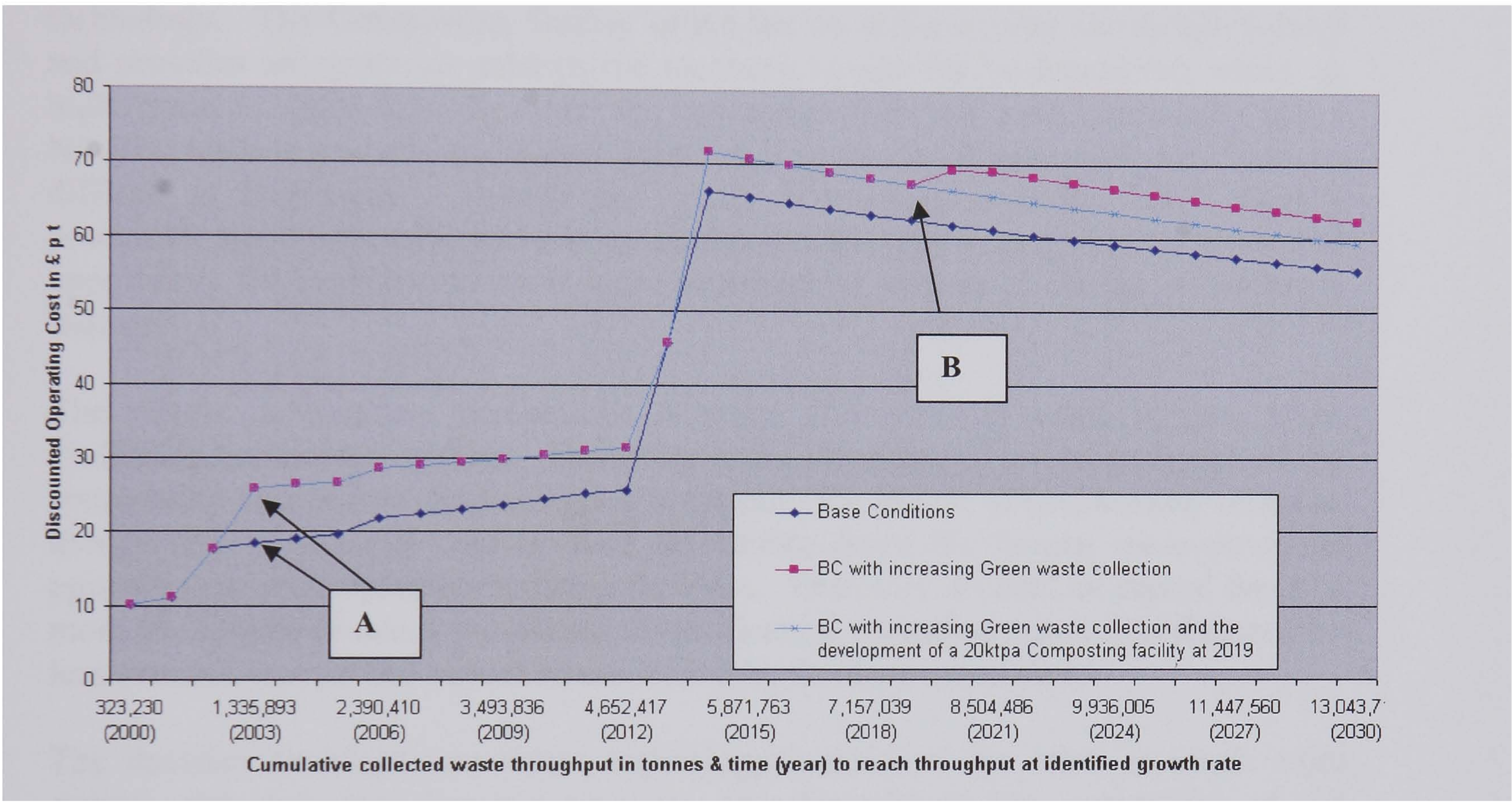


Figure 7.2 – Technology change through increase collection of green waste and the development of a 20ktpa Composting facility in 2020 with fixed landfill capacity, discounted at 3.5%

Figure 7.2 shows:

- Point A – Net unit costs in general for the collection of Green waste increase the overall cost of strategy. The additional costs of Green waste collection, transportation between the MRF and the Composting facility increase costs by about £7-8 pt, this is despite the compost bringing in revenue of £7 pt. The difficulty is that a large percentage of compost, up to 50% in tonnage is lost through degradation or rejection. Therefore the waste undergoes additional collection cost, transportation and sorting unnecessarily.
- Point B - Composting capacity will be reached at 2019 if collection of green waste is expanded to the whole of the Bedfordshire sub-region when modelled with the assumed 2.7% annual growth in waste generation. When a 20ktpa composting facility is modelled to be operational by 2020 net unit costs are stable at £66 pt compared to £69 pt if composting capacity is exceeded.

Both composting and plastic waste diversification have minor and insignificant impacts on the wider system. It is easier to adopt the Plastic diversification technology change due to the lack of need for planning permission. For example the Bedfordshire on Sunday newspaper (February & March, 2004) highlighted the local opposition to the proposed 42ktpa Composting facility in Wilden, Bedfordshire. The facility was already planned as part of Bedfordshire's 2000 waste strategy but Wilden Parish Council opposed the plans because of traffic access problems, unsightly intrusion, odour and fears over leakage. With opposition to already planned and agreed composting facilities the development of additional facilities is open to further opposition.

This example highlights the conflict between financial and strategic objectives of new technology. The Composting facility offers the most financially favourable benefit and provides an option to achieve the recovery targets for biodegradable waste, as highlighted in Table 6.3. However the opposition from the local community and a NIMBY attitude towards any waste facility makes the development of such facilities difficult to implement. Though the Plastic diversification at the MRF offers a potentially more expensive technology option it offers greater potential for change as opportunity for implementation is less obstructed by barriers to change in the waste industry.

The results demonstrate competition between short-term planning options when evaluating technology options. Based upon the technology cost performance of the composting and plastic diversification scenarios, the plastic diversification scenario, though higher financial cost is more favourable given the human socio-economic opposition to developing composting facilities. Therefore it could be argued that it is more favourable to adopt the plastic diversification technology as it is influenced by less external factors that cannot be controlled by the decision-maker.

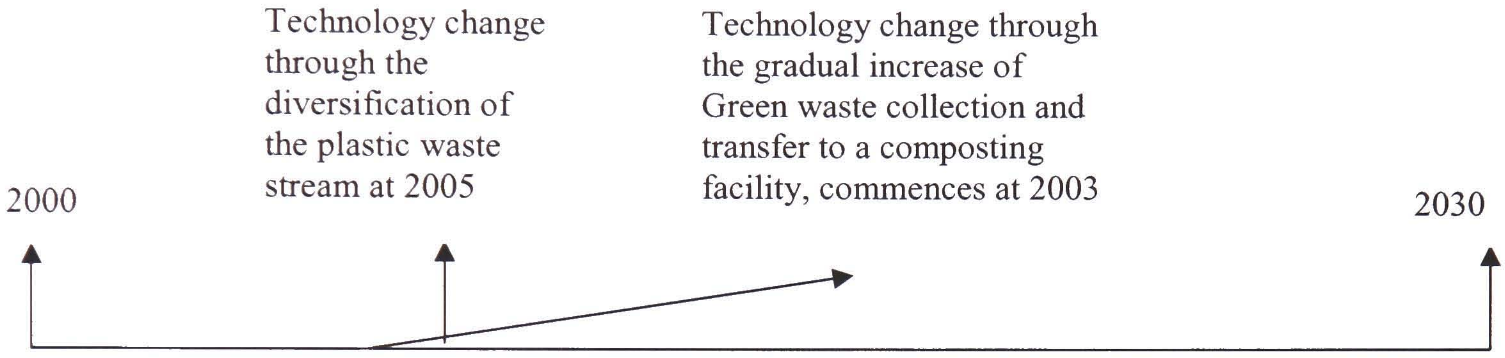
The decision to adopt one waste technology instead of the other is much more complicated than this scenario suggests and depends on the perspective of the decision-maker. Further uncertainty is associated with the location and extent of markets for recycled plastic waste or the composted 'green' waste. If the decision-maker adopts the composting technology, their resources might be better invested in gaining planning permission and securing markets for the produced compost material. If the decision-maker adopts the plastic diversification technology, their resources might be better aimed towards maintaining efficiency of the plastic sorting technology and securing markets for the recycled material. Depending on the skills of the decision-maker the timing of technology change and the evaluation of technology options might be different. In this waste technology example the key skill in the decision making process might be an understanding of the plastic and compost markets.

The evaluation between the plastic diversification technology and the composting technology raises further issues of the difference between risk and uncertainty that were identified in Chapter 5, section 5.2.4. Short-term technology options are perceived as low risk technology, given their low impact on the wider system, their low cost and the ease with which they can be incrementally integrated within a waste management strategy. As described in Chapter 4, section 4.2.4, risk and uncertainty are different concepts. These perceived low risk technologies are still influenced by uncertainty, for example uncertainty over the markets for the recycled or composted material. If the key variables to uncertainty can be controlled or limited, the uncertainty has less influence on the technology performance. In the composting versus plastic diversification example if contracts for the recycled or composted material can be secured the evaluation of the technology options might be different.

7.2.3 Technology change through the increase in Green waste collection and the diversification of the Plastic waste.

Why model this scenario?

- To meet the 2006 statutory target through diversification of existing technology
- To investigate the impact of the aggregation of sequences of technology change against the dis-aggregation of technology options.



Scenario 7.4 - Time horizon of technology change of Green waste collection and Plastic diversification i.e. two phase technology change

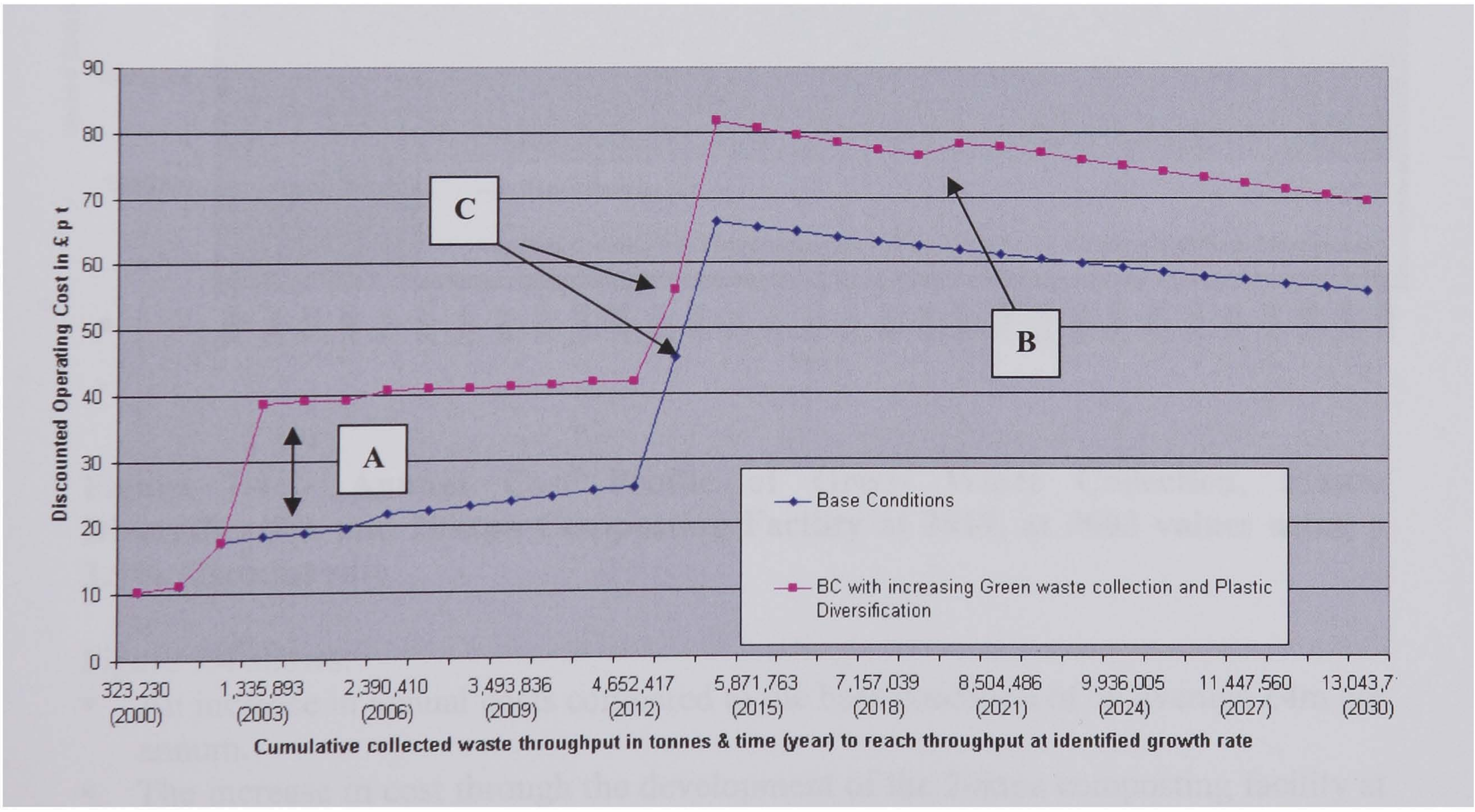


Figure 7.3 – Discounted operating cost through variation to the diversification of plastic waste and the collection of green waste at 3.5% discount rate

Figure 7.3 shows:

- Point A – Net unit costs increase from approximately £19 pt to £39 pt (at 2003 values) towards meeting the 25% statutory target for recycling and composting of household waste stream through the collection of Green waste and Plastic waste diversification.
- Point B – Composting capacity is still exceeded at 2019.
- Point C – The slight delay in growth of net unit cost at 2013 marks the delaying of landfill capacity being exceeded as waste is diverted from landfill to the composting facility.

These costs are converted into annual cost profiles to highlight the cost of compliance to legislation and waste policy. Given that the UK waste industry is predominantly operated by private waste companies the costs will increase to reflect the need to make a profit. In the UK waste industry the profit margin currently applicable is around 2% (Lowe, 2003).

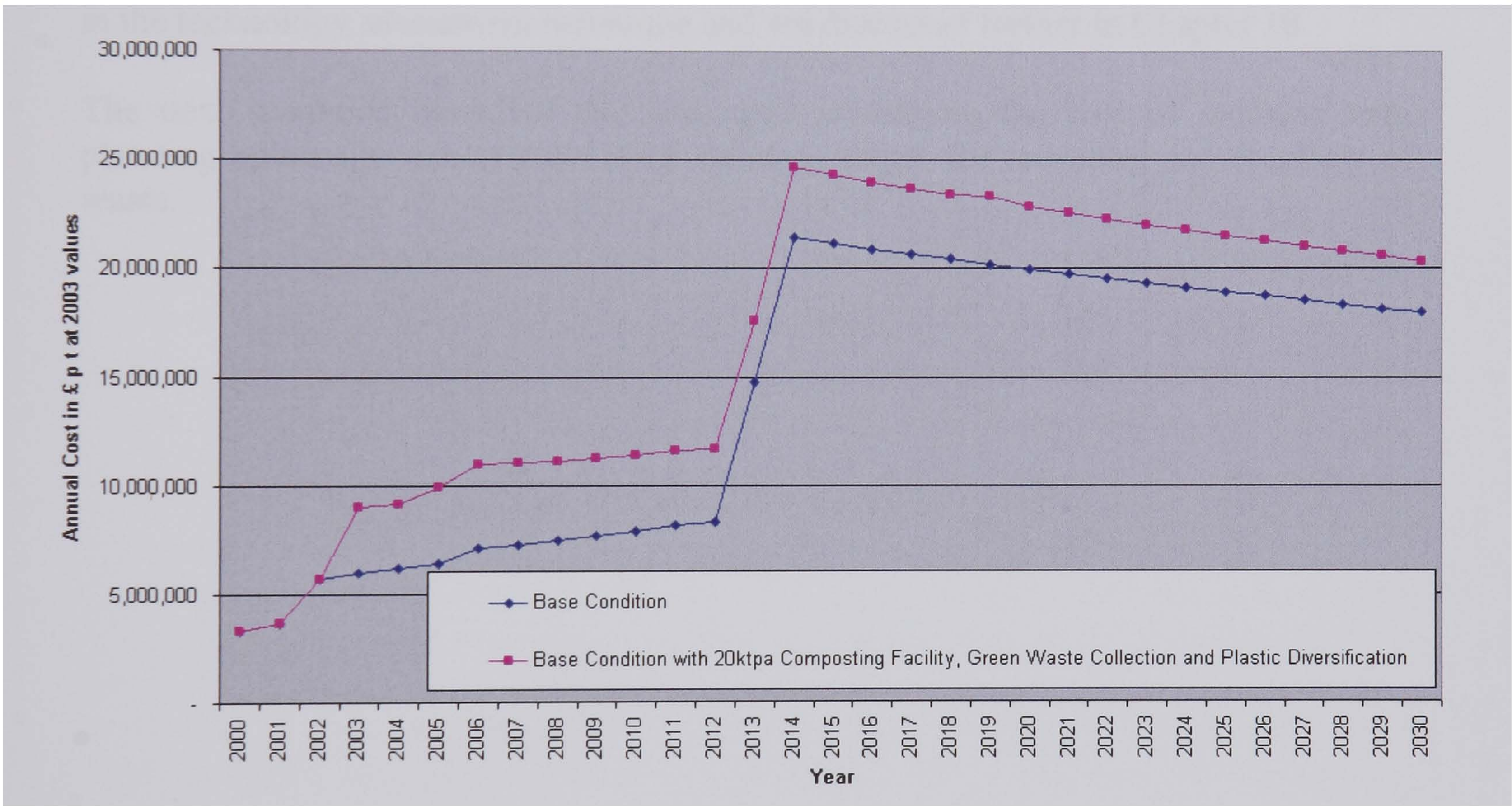


Figure 7.4 - Annual Cost Profile of Green Waste Collection, Plastic Diversification and 20ktpa Composting Facility at 2019, at 2003 values using a 3.5% discount rate

Figure 7.4 shows:

- An increase in annual costs compared to the base condition of on average £4m per annum.
- The increase in cost through the development of the 20ktpa composting facility at 2019 has only minor significance on cost.

7.2.4 Analysis of Short-term options to achieve 2006 Statutory target for recycling and recovery

As identified in Figure 7.4 the net cost increase to comply with the 2006 Statutory target for the Bedfordshire sub-region will be approximately £4m annually. (N.B. These costs are not the total cost but the net cost). These cost predictions are based upon adopting technology change through increasing Green waste collection throughout the Bedfordshire sub-region and adopting plastic diversification technology at the Materials Recovery Facility. As identified earlier this cost does not reflect the additional costs that will be added to the annual costs as the private waste companies that operate the waste management system in the Bedfordshire sub-region seek to make a profit or return above these costs.

These costs anticipate the maximum recycling and recovery of the green waste and plastic materials. In reality maximum recycling rates are unlikely to be achieved as recycling and recovery rates are affected by operational issues such as technology inefficiency caused by contamination, technology shutdowns, accidents and public participation rates etc (as described in Chapter 3). These issues should be considered in the technology assessment technique and are discussed further in Chapter 10.

The next scenarios modelled and presented investigate the cost of medium term planning options to achieve the 2015 statutory target for recycling and recovery of waste.

7.3 Medium-term planning technology

Medium-term planning technology options include the Mechanical Biological Treatment process 'Ecodeco'. This section will investigate technology change through the introduction of the 'Ecodeco' process either as a single technology change event or as a sequence of multiple phased technology investment.

Why choose MBT 'Ecodeco' to assess impact of medium-term technology options?

- Ecodeco is selected as it offers opportunities to meet legislative targets particularly relating to the diversion of biodegradable waste from landfill. Therefore through modelling different technology options incorporating the MBT process the extent to which environmental policy impacts technology performance can be investigated.
- It is a proven technology in Italy with operational data available with technology change through the transfer of knowledge so there is less uncertainty associated with the technology. The extent to which risk allocation associated with technology change can be investigated.
- It treats unsorted waste streams and can be viewed as an add-on technology. This means it doesn't have to widely disrupt the existing infrastructure for waste strategy. Therefore the implementation of technology change can be varied easily to investigate the impact of aggregation and timing of technology change on technology performance. Further investigation into the aggregation of different technology changes can be researched as the technology offers an opportunity for sequential technology change in that it can be built with or without on-site incineration of the Refuse Derived Fuel, as described in Chapter 3.
- A single 60ktpa Ecodeco unit is the smallest sized unit that can be developed. The smallest sized unit might be developed in reality as a demonstration and pilot unit for technology change through the Ecodeco process.

The capital costs of the Ecodeco process are estimated at £8m per 60ktpa unit. The maintenance cost of these units is £1m every 5 years. Planning costs are in the region of £250,000 per project i.e. planning costs for an Ecodeco plant and an on-site EfW facility are 2*£250,000 = £500,000. When building an Ecodeco unit it is favourable to pre-sort all waste prior to reception through a MRF technology. The building of additional MRF capacity is assumed to be included in the costs of developing the Ecodeco process.

As described in Chapter 3 the MBT 'Ecodeco' process produces Refuse Derived Fuel pellets that are incinerated at an Energy from Waste facility. This incineration can occur on or off-site and can be developed as a sequential phasing of technology development. For example the initial stage of development can be the Ecodeco process with transportation of the RDF off-site, with the second phase of development to include and on-site EfW facility. The phasing of technology change can assist in overcoming some of the barriers to technology change such as the gaining of planning applications as the technology change is split into smaller sequential events. The cost of developing a 200ktpa EfW facility on-site to incinerate the RDF is estimated at a capital cost of £43m and a unit (operating + maintenance) cost of £28.20 pt. Planning costs are assumed to be £250,000 per project with maintenance costs of £1m every 3 years and a major overhaul after 10 years of £10m (CIWM, 2003).

Using the waste flows identified in Figure 6.1 the optimum rate of diversion of rate from landfill to a 60ktpa MBT 'Ecodeco' facility is 14% of unsorted household collected waste in the Bedfordshire sub-region. If aggregation of technology options Plastic diversification, Green waste collection and the diversion of unsorted waste to a 60ktpa MBT 'Ecodeco' process are combined, significant progress towards the 2015 statutory target of 33% recycling and recovery is achieved. For example:

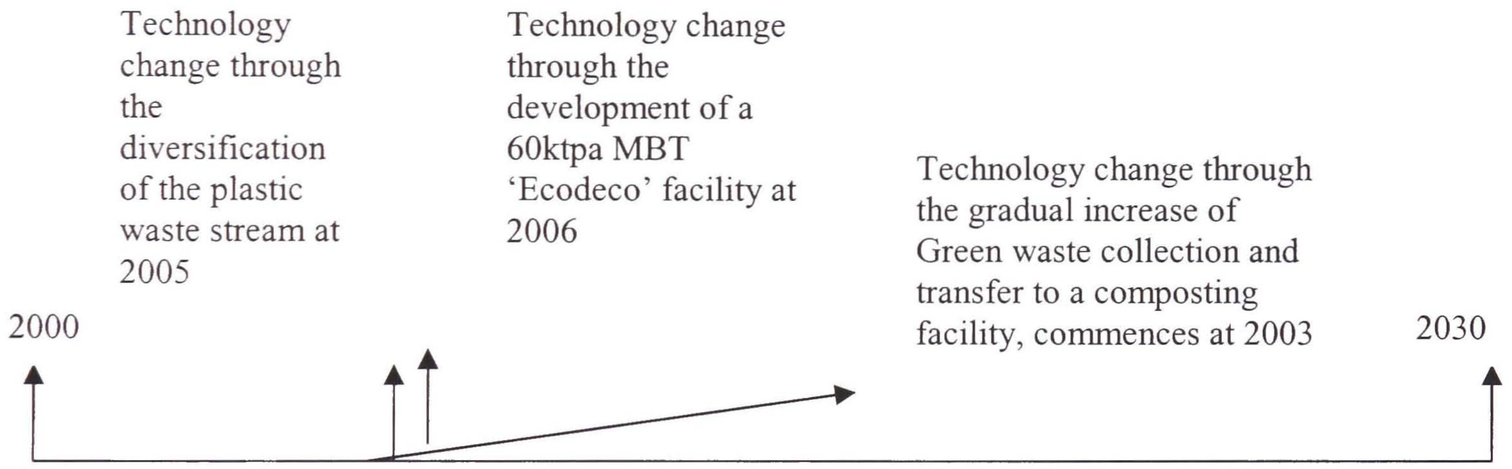
(i) 10-14% of unsorted waste is diverted to MBT 'Ecodeco'
(ii) 7-10% Composting
(iii) 5-7% Plastic diversification sorting
(iv) 5-7% recycling and composting currently achieved by the waste strategy in the Bedfordshire sub-region

Through modelling the aggregation of these scenarios the cost of achieving waste policy can be identified and the process of innovation investigated.

7.3.1 Technology change through the development of plastic diversification, green waste collection and a 60ktpa MBT 'Ecodeco' facility

Why model this scenario?

- To meet the 2006 statutory target in an incremental manner of least change to the system based upon existing waste strategy plans in the Bedfordshire sub-region
- To enable assessment of the aggregation of technology options allowing investigation as to the extent to which aggregation of technology can assist in overcoming conflict to technology as in Chapter 2, Table 2.2.



Scenario 7.5 – Time horizon the recycling through diversification of the plastic waste stream, the composting of collected 'green' waste and the diversion of unsorted waste to a 60ktpa MBT process.

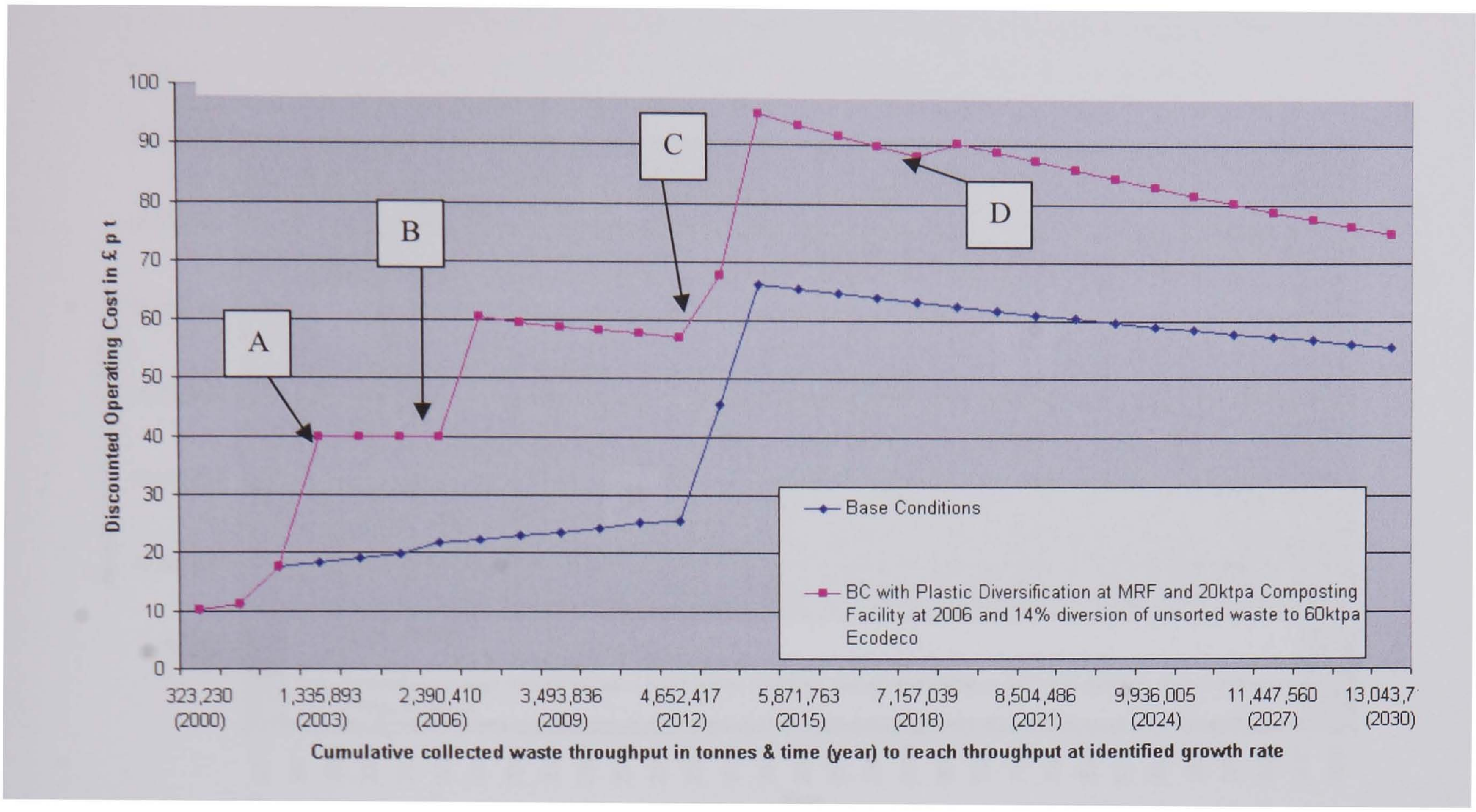


Figure 7.5 – Discounted unit cost at 3.5% discount rate of technology change through Plastic waste diversification at MRF, Green waste collection with composting and diversion of 14% of unsorted waste by a 60ktpa MBT 'Ecodeco' process with offsite incineration of RDF

Figure 7.5 shows:

- Point A – The net unit costs increase from £19 pt to £39 pt in 2003 (at 2003 values) as Green Collection and Plastic diversification technology changes occur.
- Point B – The costs increase from £40 pt to £60 pt in 2006 as MBT becomes operational.
- Point C – The delay in the landfill capacity being exceeded as 25% of collected waste is diverted from landfill. This is only minor given the amount of imported waste to landfill in the Bedfordshire sub-region waste strategy.
- Point D – The composting facility is exceeded and new facility space is needed to process the Green waste collection.

These costs are converting into annual cost profile to highlight the timing of costs and the scale of needed capital investment.

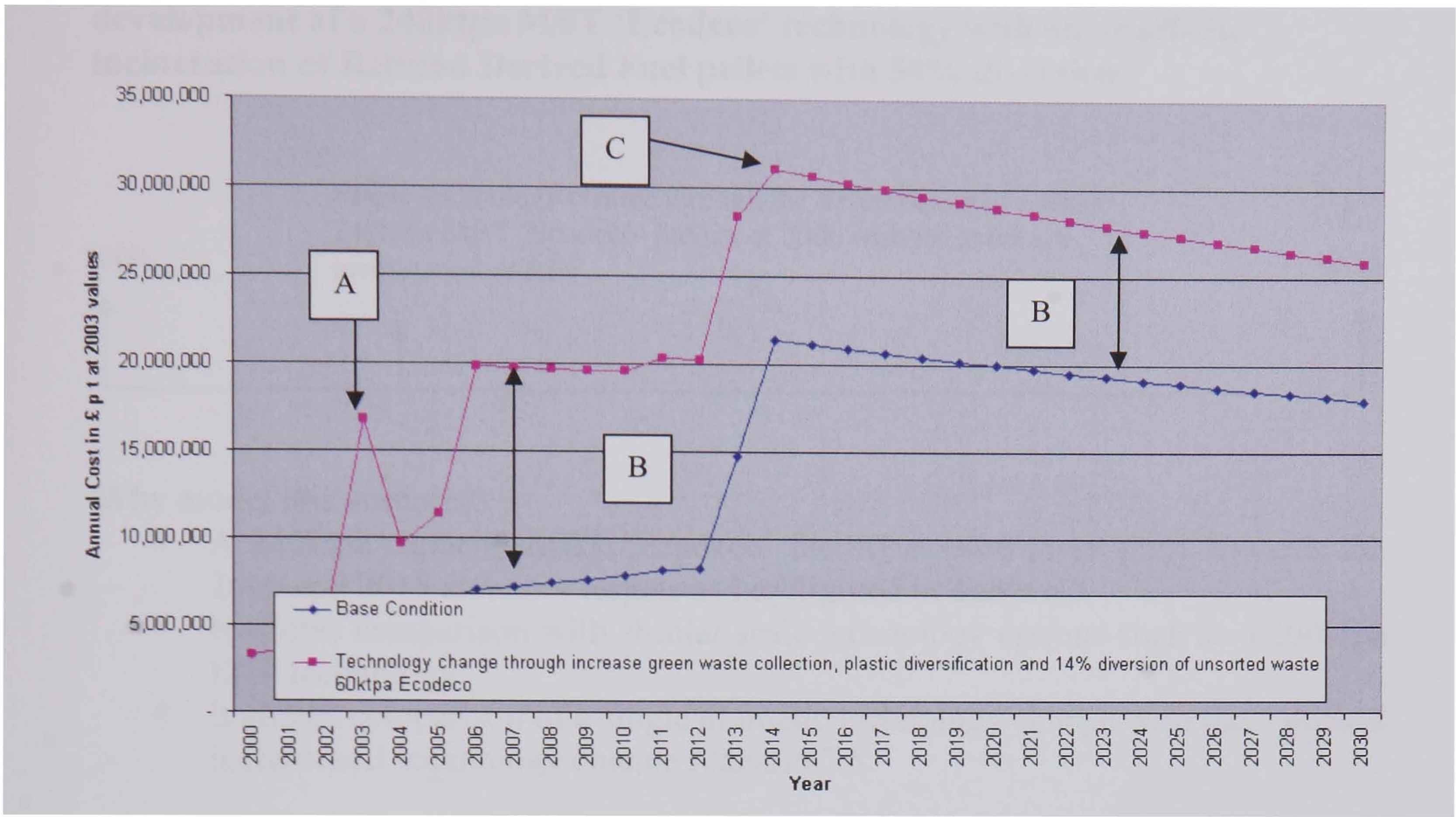


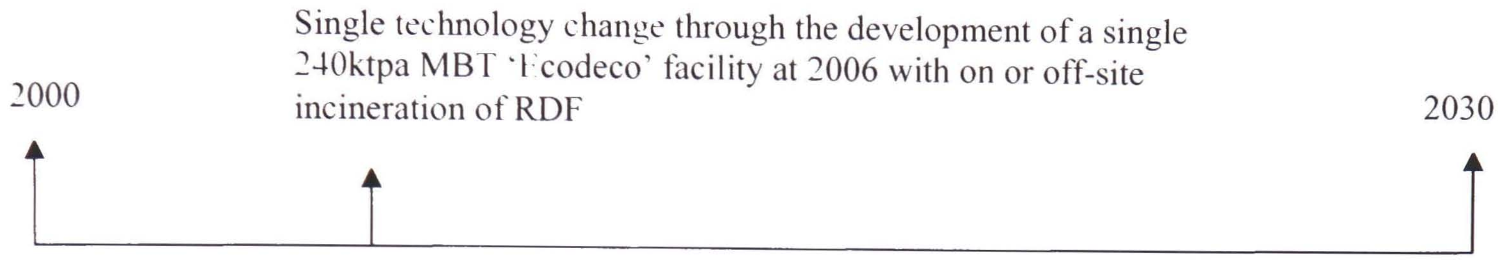
Figure 7.6 - Annual Cost Profile of Plastic Diversification, Green Waste Collection with 20ktpa composting facility at 2019 and 60ktpa MBT Ecodeco facility treating 14% of unsorted waste at 3.5% discount rate

Figure 7.6 shows:

- Point A – The initial capital investment in the MBT facility at 2003 causes costs to peak at £16.5m. Capital costs are assumed to occur at 2003 though in reality payment of capital costs will be phased during the planning and construction process as described in Chapter 5.
- Point B - Costs are significantly higher across the time period of assessment. At 2007 the annual cost is around £13/14m greater than maintaining the base condition strategy. At 2023 the annual cost increase is around £7/8m (at 2003 values). Cost difference between the base condition and the 3 phased technology change scenario decreases as the percentage increase in costs is less than the discount rate (as explained in Chapter 6).
- Point C - Costs rise to a maximum of £31m at 2015 (at 2003 values) when landfill capacity is exceeded.

The scenario is compared with other single new technology scenarios that would achieve the same statutory target for recycling and composting of household waste.

Scenario 7.6 – Time horizon for single phase technology change through the development of a 240ktpa MBT 'Ecodeco' technology with on or off-site incineration of Refused Derived Fuel pellets with 50% diversion



Why model this scenario?

- A 240ktpa capacity MBT 'Ecodeco' facility needed to progress towards the 2006 and 2015 statutory targets as highlighted in Table 6.3.
- It allows comparison with similar scale technology options such as a 200ktpa EfW technology.
- It allows comparison of a single dramatic technology change with the 3 phased incremental technology change scenario 7.5.

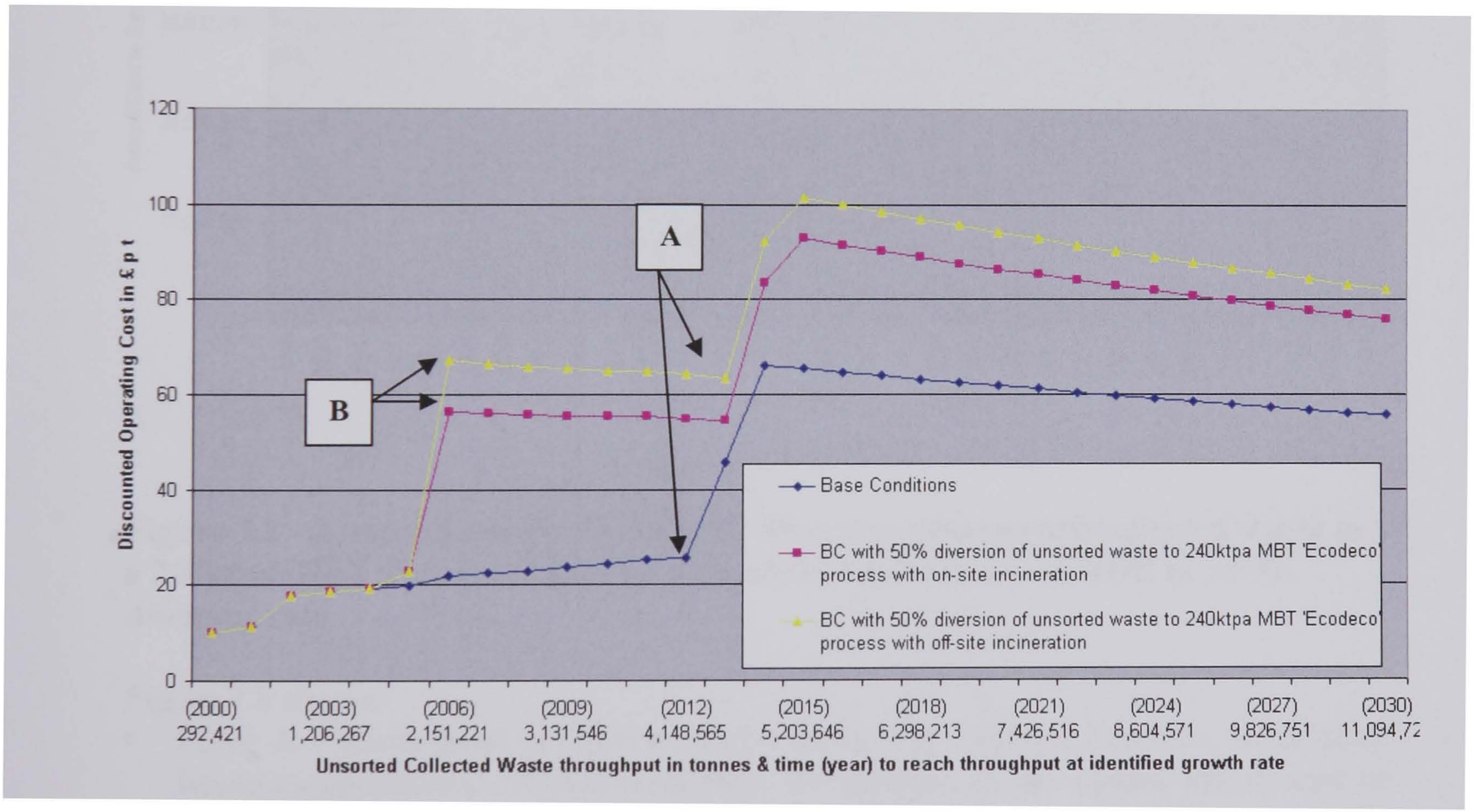


Figure 7.7 – Discounted operating cost of the development of a 240ktpa Ecodeco facility with or without onsite incineration through a 200ktpa EfW of the produced RDF pellets, processing 50% of unsorted collected waste, operational by 2006.

Figure 7.7 shows:

- Point A - The graph displays the delay in the reaching of landfill capacity in the Bedfordshire sub-region from 2012 to 2013 as waste is diverted from landfill.

- Point B - With on-site incineration of RDF the additional net unit costs associated with developing an EfW facility are less than the transportation of the RDF to an external EfW facility (i.e. at Dundee) plus the gate fee for the RDF at the EfW facility. For example £56 pt compared to £67 pt in 2006, £91 pt compared to £100 pt in 2016 (at 2003 values). RDF is a refined form of waste, improving its potential for incineration and energy recovery than unprocessed waste therefore it has potential value as an energy fuel. The difficulty is the lack of existing markets for the RDF pellets in the UK as the technology to incinerate the pellets is not widely available at present (GLA, 2003). Therefore the 'market' for the RDF pellets is not yet established in the UK and the companies offering technology to incinerate the RDF are in a strong position when determining the gate fee for RDF.

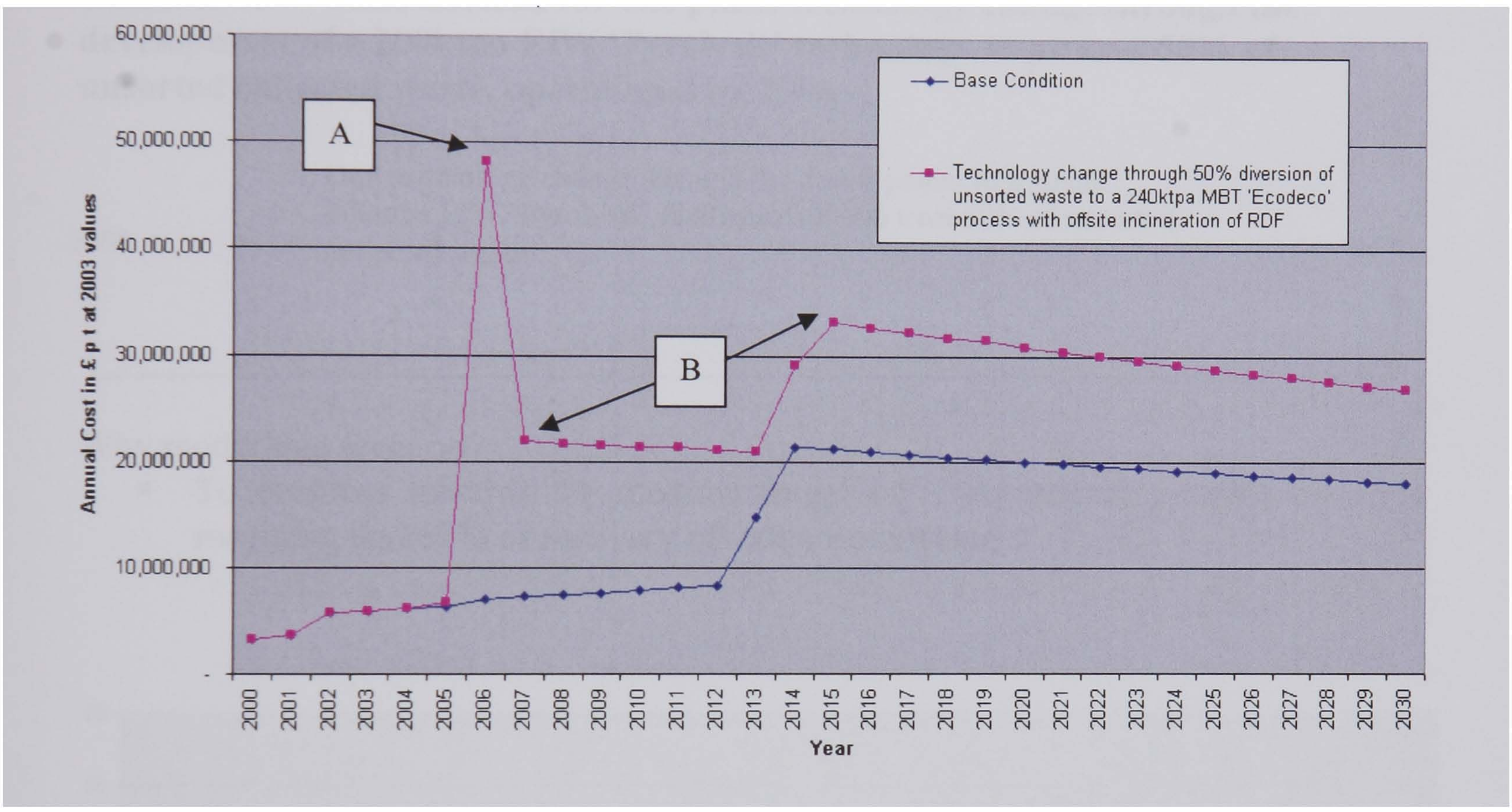


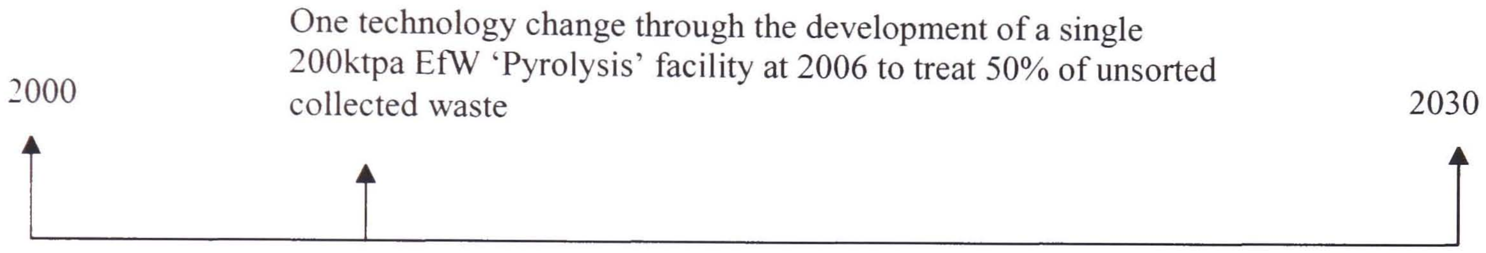
Figure 7.8 - Annual Cost Profile of 50% diversion of unsorted collected waste to a 240ktpa MBT 'Ecodeco' facility with offsite incineration of RDF at 3.5% discount rate

Figure 7.8 shows:

- Point A - Costs peak at 2006 at £49m when the 240ktpa Ecodeco technology becomes operational. Costs peak later in response to the capital investment as given that the technology is larger scale longer planning and construction time is needed to develop an operational facility. As identified earlier though in practice costs are phased, in these results it is assumed capital costs occur at a single point in time. This is as the main purpose of the annual cost profiles is to identify the cost of compliance to policy and though phasing capital payments and other accounting practices or techniques will affect and maybe reduce costs, the profiles give a good understanding of the scale of costs involved.
- Point B - Annual costs increase on average between £13 to £9m ranging from 2007 to 2030. From £21m in 2007 to £33m in 2016.

The results demonstrate the impact on technology performance of the MBT 'Ecodeco' process due to the barrier created by the lack of markets for the RDF. In determining the opportunity for technology change through the MBT process the quality of the RDF, the transport distance to the EfW plant, the gate fees of imported waste and the existence of incineration contracts of the generated RDF, all need to be considered. If the EfW facility is developed on-site i.e. internally as part of the same integrated technology, the net unit costs are lower as the gate fee is lower than exporting the waste to an external incineration facility (under present market conditions). If the market for RDF becomes more competitive, off-site incineration of the RDF could become more favourable as instead of paying a gate fee for the RDF it might generate revenue as a fuel.

Scenario 7.7 – Time horizon for one phase technology change through the development of a 200ktpa EfW 'Pyrolysis' technology to process 50% of unsorted collected waste, operational by 2006.



Why model this scenario?

- To progress towards the medium target i.e. 2015 statutory target for 33% recycling and 67% of recovery of value from waste.

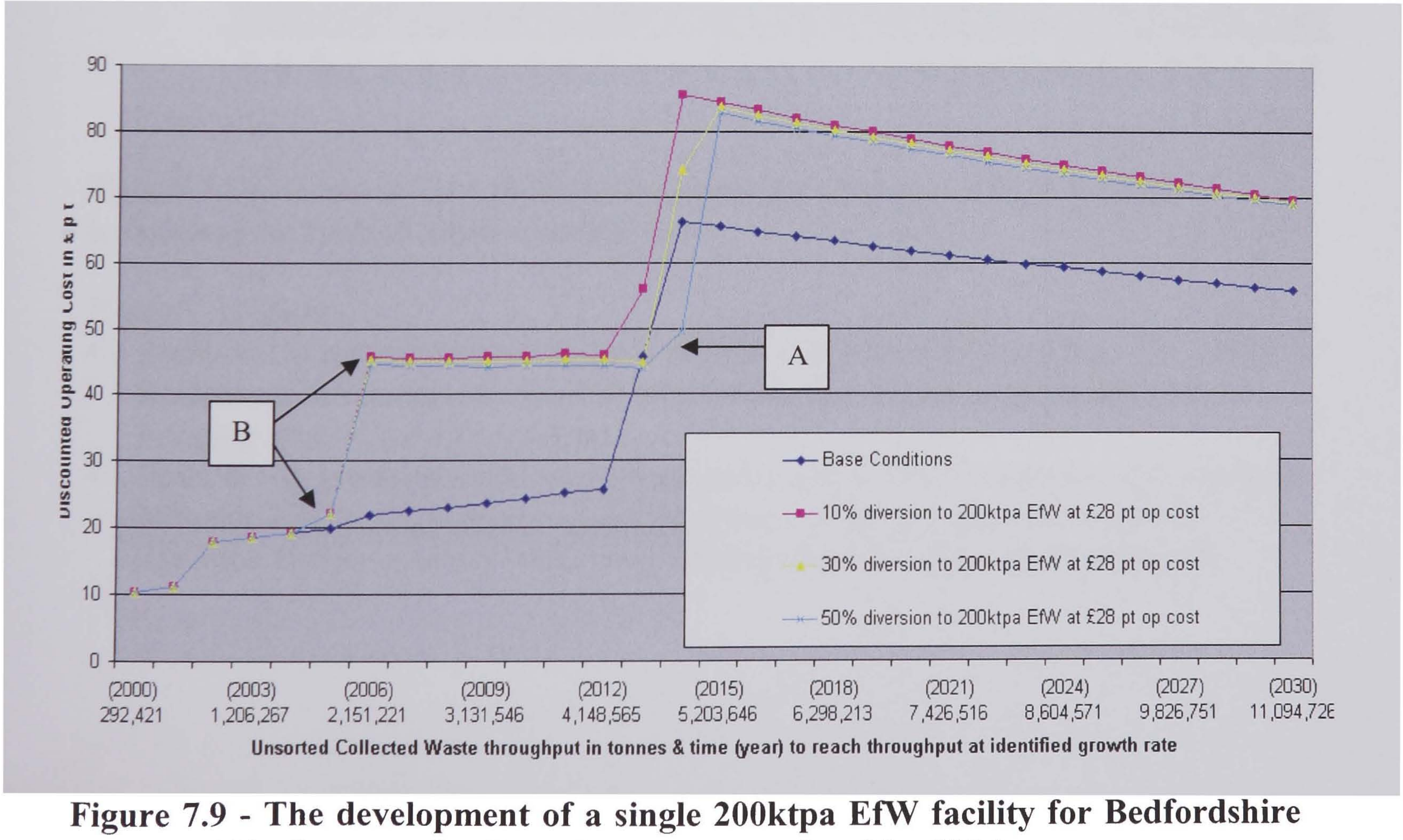


Figure 7.9 - The development of a single 200ktpa EfW facility for Bedfordshire to treat 50% of unsorted collected waste, operational by 2006

Figure 7.9 shows:

- Point A – For 50% diversion of unsorted collected waste. A timing delay of 1 year to reaching maximum waste capacity of landfill as waste is diverted to the EfW facility.
- Point B – For the 200ktpa EfW new technology option net unit costs increases from approximately £20 pt to £46 pt in 2006 (at 2003 values).

The net unit costs associated with the EfW technology are much lower than both the three phase (plastic, green and MBT) technology aggregation scenario 7.5 and the one or two phase MBT technology change options described in scenario 7.6.

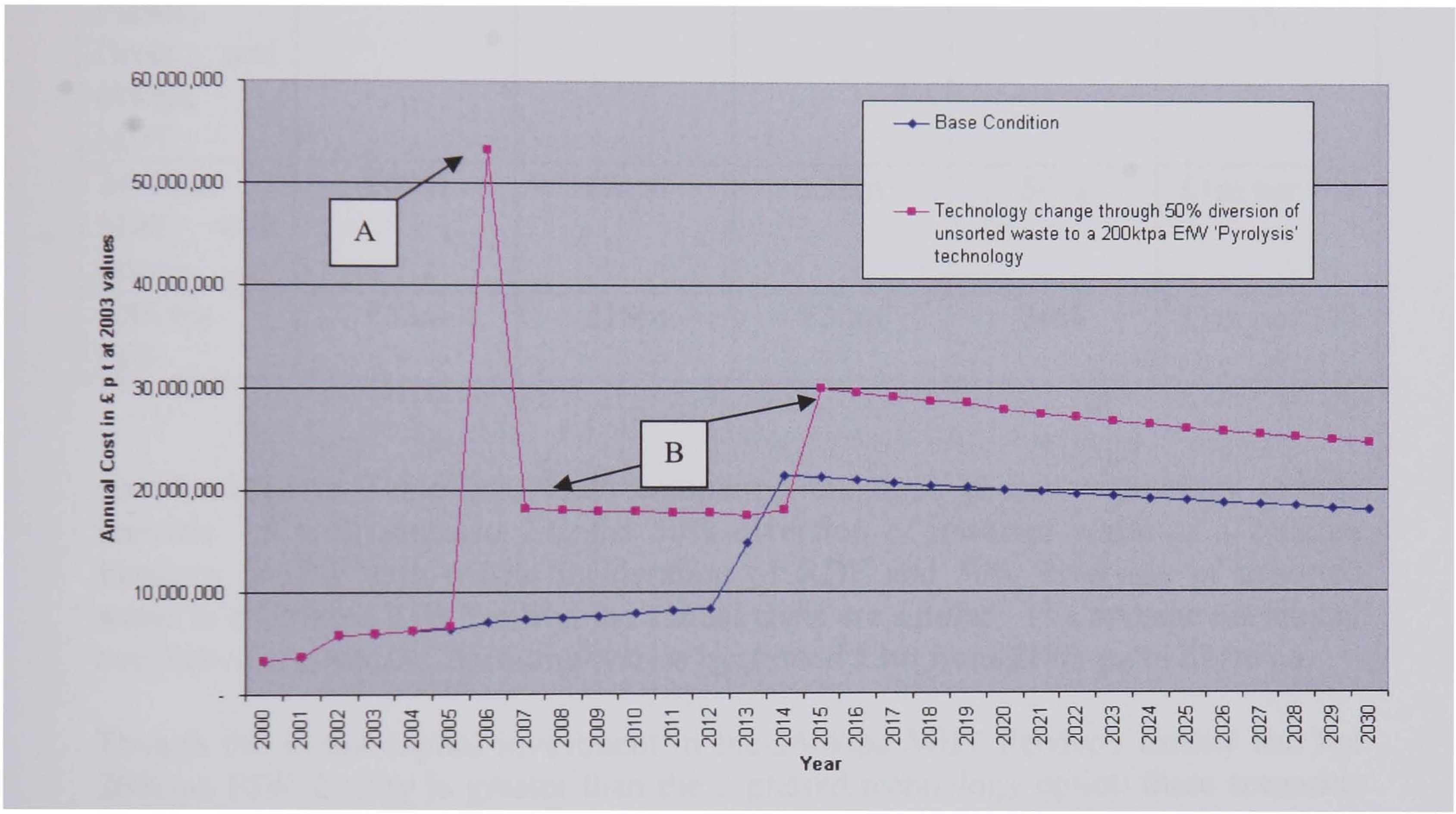


Figure 7.10 - Annual Cost of 50% diversion to a 200ktpa EfW 'Pyrolysis' technology at 2006 at 3.5% discount rate

Figure 7.10 shows:

- Point A – A maximum peak in costs at 2006 of £53m at 2003 values. The initial investment in the capital cost is delayed to account for planning delays and the building time of the EfW facility.
- Point B – A lower annual cost increase compared to early scenarios. For example between 2007 and 2014 cost are stable around £19m compared to Scenario 7.7 (240ktpa Ecodeco) where costs were around £21m for the same time period.

7.3.2 Analysis of Medium–term technology options to achieve the 2015 Statutory target for recycling and recovery of MSW

Table 7.1 - Comparison of Scenarios 7.5, 7.6 and 7.7 to achieve 2015 Statutory Target for Recycling and Recovery of 33% of waste

Scenario	Cost in capital investment year	Ave Annual Cost between 2006 and 2016	Annual Cost at 2016	Max Recycling and recovery % increase achievable	Approx Cost per % increase in recycling and recovery
3 Phase – Plastic, Green and 60ktpa MBT	£16.5m	£20m	£31m	33%	£0.5m per 1%
240ktpa MBT with offsite	£49m	£21m	£32m	50%	£1m per 1%
200ktpa EfW	£53m	£18m	£30m	50%	£1m per 1%

As identified in Table 7.1, when comparing the three phased technology change scenario 7.5 with scenario 7.6, the 50% diversion of unsorted waste to a 240ktpa Ecodeco facility with offsite incineration of RDF and 50% diversion of unsorted waste to a 200ktpa EfW facility, the annual costs are similar. The average net annual cost between 2006 and 2016 only varies by around £3m from £18m pa to £21m pa.

Though the initial capital investment in the 240ktpa MBT Ecodeco facility and the 200ktpa EfW facility is greater than the 3 phased technology option these scenarios process 50% of the unsorted collected waste material. This is compared to the 33% recycling and recovery of the unsorted collected material using the 3 phased technology change scenario. Given that these are the maximum values and as identified earlier the maximum recycling and recovery rates are unlikely to be achieved, the 240ktpa MBT scenario and the 200ktpa EfW scenario might be viewed by many as the more realistic option to achieve the 2015 statutory target.

The results identify the conflict between the human socio-economic and the operational objectives of technology. As was identified in Chapter 1, strategy in the UK is often based upon a compliance approach rather than a proactive approach to go above and beyond the next legislative target. In evaluating opportunities for technology innovation the assessment technique should consider the efficiency of performance of technology given the uncertainty associated with integrated waste management systems. Technology designed to perform beyond the statutory targets the technology provides an increased ability to sustain performance over time (i.e. it is less affected by uncertainty, it is more flexible) but this comes at additional cost. Chapter 10 discusses this trade off between flexibility and cost further investigating the extent to which this is a limitation of technology assessment techniques and the design of policy.

The results demonstrate that the setting of targets for recycling and recovery is a weakness of waste policy (as argued in Chapter 1). The cost profiles show that the cost of compliance to increasing recycling and recovery targets is not linear to the increase in recycling and recovery rate. Assuming annual costs are equal between the scenarios at approximately £20m pa between 2006 and 2015. By increasing the recycling rate from the current 5-7% to 33% the average capital investment cost per 1% of recycling & recovery is £0.5m per 1% (using the 3 phased technology option scenario). To increase recycling and recovery rates a further 17% i.e. 33% to 50% using the 240ktpa MBT process or the 200ktpa EfW process, the average capital investment per 1% recycling & recovery would be approximately £1m pa.

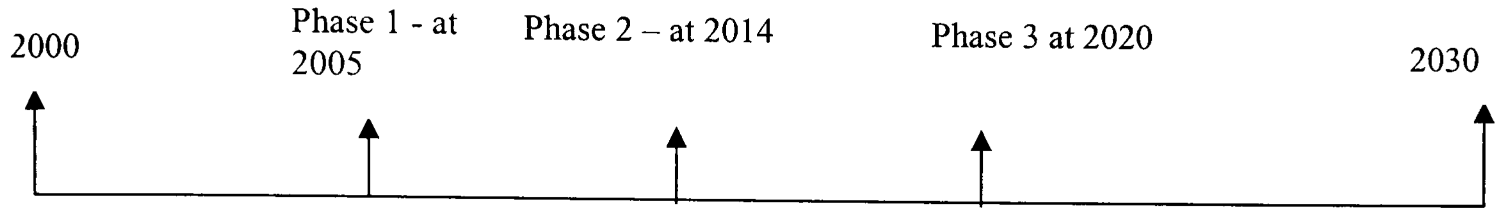
As demonstrated by scenario 7.7 the development of a 200ktpa EfW facility in the Bedfordshire sub-region produces the lowest net unit annual cost of £18/19m between 2006 and 2015. Given the opposition to EfW as described in Chapter 4, due to the NIMBY public attitude and the perceived associated health risks with this technology, gaining planning permission for such facilities is extremely difficult. The model results demonstrate that in order to overcome the barriers to such technology, due to these human socio-economic factors, technology at higher annual net unit cost will need to be developed. This could be scenario 7.5 the combination of plastic diversification at the MRF, composting of increasingly collected green waste and the development of a 60ktpa MBT facility. This scenario incurs higher annual net unit costs around £20m pa between 2006 and 2015. Therefore the human socio-economic factors are having a direct impact on the cost of technology and waste strategy.

It could be argued that as the additional costs are a result of public opposition the costs should be borne by the public through increased charging for waste services rather than the waste company providing the service. The public opposition in Bury (MEN, 2004) highlights the difficulties in increasing charges for waste management. There the household collection scheme requires the public to sort waste into four different containers with different containers collected on alternative weeks. Opposition to the scheme has included questions as to why a reduced quality of service is being provided yet council taxes are increasing? The results allow the costs and impact of such human socio-economic opposition to be demonstrated, informing the decision stakeholders of their impact on strategy.

7.4 Long-term Planning Technology options

This section investigates the cost of long-term planning technology options using the need to comply too the pre-treating all waste prior to disposal to landfill, as stated in the Landfill Directive (as described in Table 1.1). Within the thesis given the categories of waste composition modelled it is assumed that the unsorted waste fraction needs additional treatment prior to disposal to landfill.

Scenario 7.8 – Time horizon for the multiple phase technology change through the development of varying sized MBT 'Ecodeco' technology to treat unsorted collected waste in Bedfordshire.



420ktpa is the maximum throughput of unsorted collected waste derived from the model given the identified annual waste generation growth rate for Bedfordshire in Chapter 6, Figure 6.1. Three scenarios to achieve the 420ktpa 'Ecodeco' capacity are modelled:

- One Phase - The development of a single 420ktpa Ecodeco facility at 2005 – single phase, dramatic, high risk associated technology change. Through developing larger scale facilities economies of scale and economies of production can be realised. This is reflected through reduced operating cost of the MBT facility from £25 pt to £20 pt.
- Two Phase - The development of a 180ktpa Ecodeco facility at 2005 followed by a second 240ktpa Ecodeco facility at 2014. The first phase of development is the earliest time the technology can be operational given the planning and design time needed. The second phase of development is timed at 2015 i.e. immediately before the 2016 statutory target date. Through developing a two phased approach some economies of scale and economies of production can be realised. The second phase of technology development would benefit from reduced uncertainty of the technology, as it will be better understood through the first phase of development. This is reflected in reduced operating costs from £25 pt to £22 pt.
- Three Phase - A sequence of three 120ktpa Ecodeco facilities using the 'just in time' principle i.e. as and when needed to meet growing waste generation i.e. at 2005, 2014 and 2020 – Multiple phase, incremental technology change. Through developing smaller technologies initially the uncertainty and opposition to technology change might be reduced. This could lead to potential savings in the planning process and reduce the opposition to new technology. It helps prevent unnecessary investment if uncertainty creates a dramatic impact on the technology performance. For example if the MBT facility was proved to emit dangerous emissions, it might be shut down immediately and the technology becomes obsolete. By delaying the investment of capital, reduced potential for capital value loss due to uncertainty over time is gained.

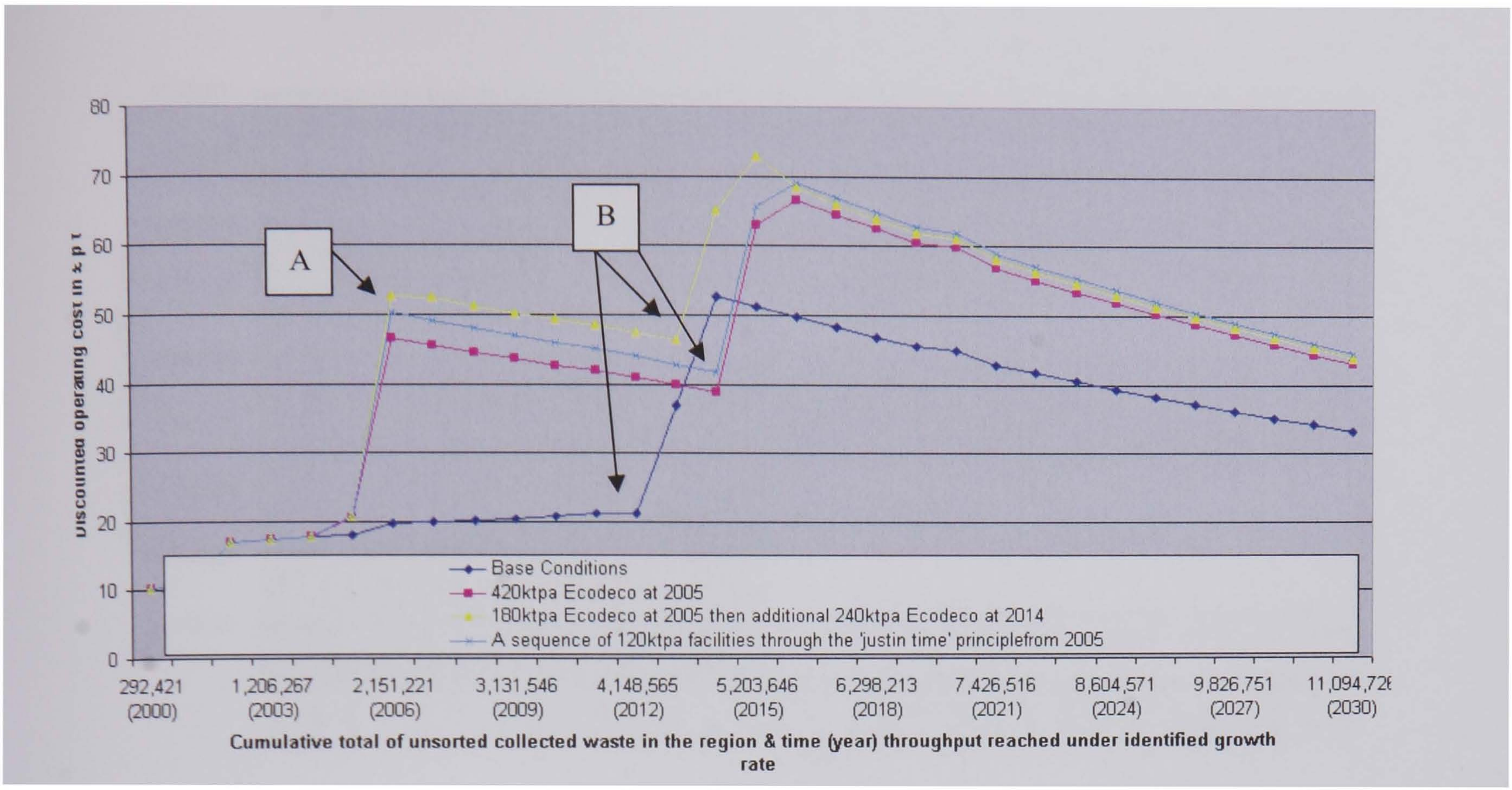


Figure 7.11 – Disocunted operating cost of variation through the development of multiple phased MBT 'Ecodeco' facilities to reach 420ktpa operating rate and treat 100% of unsorted collected waste in Bedfordshire at 3.5% discount rate

Figure 7.11 shows:

- Point A – The increase in net unit costs from the base condition to treat the unsorted collected waste by the Ecodeco process. The costs vary depending on the sequence of technology change adopted. With different sizes of facility developed economies of scale and economies of production result in lower operational costs. For example the costs associated with operating a 420ktpa MBT facility are lower than the costs of operating a series of 120ktpa facilities £47 pt against £50 pt in 2006 (at 2003 values).
- Point B – The costs of the 180ktpa MBT facility followed by the 240ktpa facility rise earlier as the capacity of the MBT facility is exceeded at 2013 before the second phase development becomes operational. Therefore the scenario incurs additional costs as waste is transferred to the MBT process and stored prior to processing. There is additional transportation cost as the waste is transferred unnecessarily to the MBT process rather than go direct to landfill.

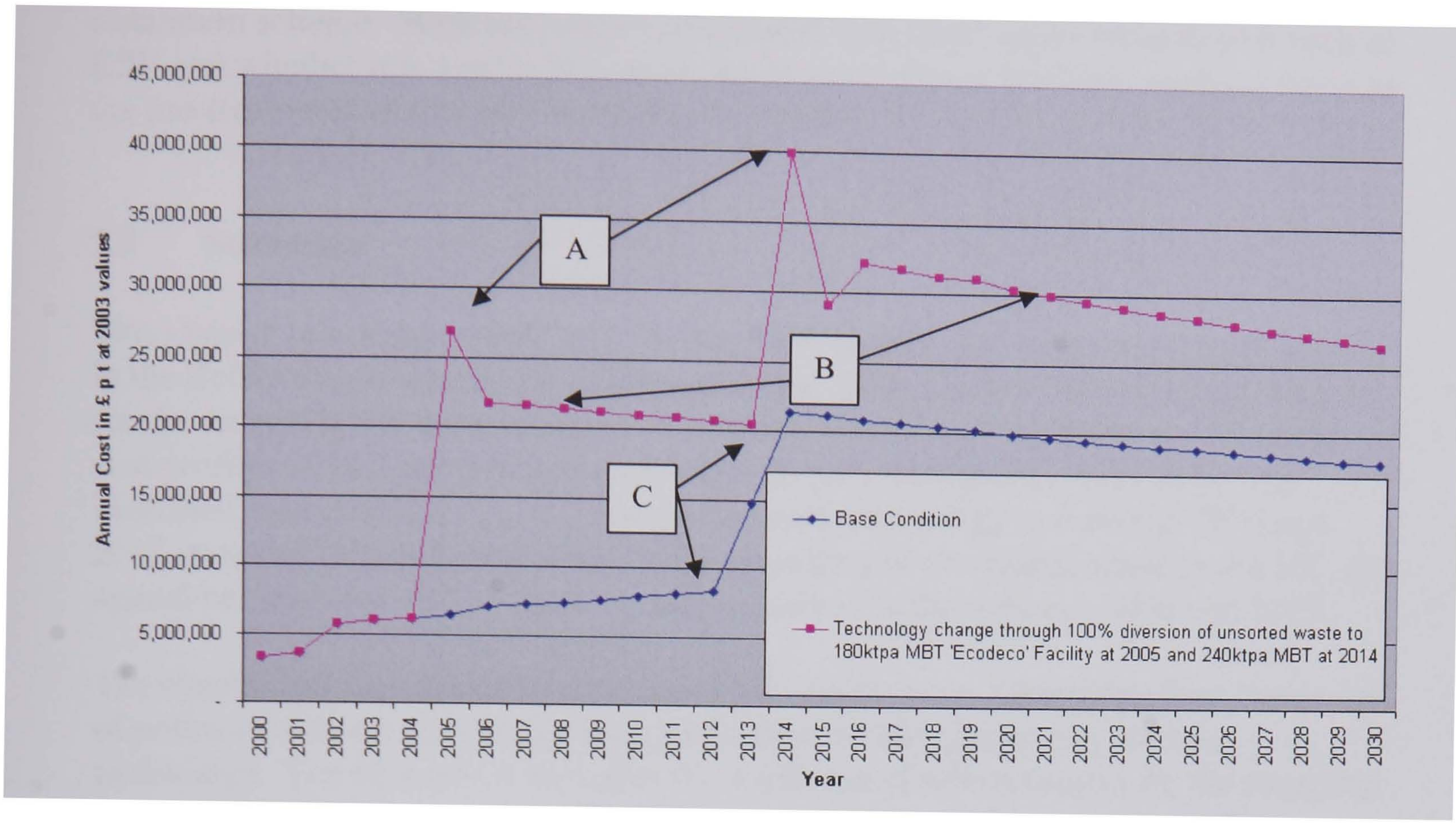


Figure 7.12 – Annual Cost Profile of technology change through 100% diversion of unsorted waste to a 180ktpa MBT Ecodeco facility at 2005 and a 240ktpa MBT Ecodeco facility at 2014 at 3.5% discount rate

Figure 7.12 shows:

- Point A – By adopting the two phased technology change option two peaks of £26m at 2005 and £40m at 2014 (at 2003 values) are identified.
- Point B – Between 2006 and 2013 annual costs are relatively stable at around £21m pa. Between 2017 and 2030 net annual costs range from £33m to £26m (at 2003 values) approximately £10m pa more than if the base condition was maintained. As identified earlier costs decrease due to the discount rate being greater than the percentage increase in costs and imported waste being reduced.
- Point C – The rising of costs caused by the landfill capacity being exceeded is delayed by 1 year as the unsorted waste is treated reducing the tonnage of waste sent to landfill as more waste is recycled and recovered as either compost or RDF through the MBT process.

7.4.1 Analysis of Long-term technology options to achieve the need to pre-treat all waste prior to disposal to landfill

The cost of compliance to the waste policy is identified as around £14/5m between 2006 and 2013 using the 420ktpa MBT facility in a two phased development. As identified in Chapter 1, one weakness of waste policy is the lack of clarification in the definitions of waste and of waste technologies. This uncertainty over the definition of waste technologies is affecting the evaluation of the pre-treatment of waste, as there is uncertainty over what constitutes a pre-treatment technology. For example if a household source separation scheme is employed does this mean that all waste has undergone pre-treatment including the unsorted waste fraction? In Chapter 3 one of the advantages of the MBT Ecodeco technology identified was that it allows a second bite at the recycling cherry, therefore implying that the first bite was the source separation scheme. With uncertainty associated with other waste technologies such as EfW and whether it is a recycling, recovery or treatment technology, applying costs to the pre-treatment of all waste is difficult to clarify.

7.5 Summary

This chapter has presented the results of modelling different waste technology options in the Bedfordshire sub-region to help attain the 2006 and 2015 UK statutory targets for the recycling and composting of household waste. The modelling results show cost profiles of strategy performance over a 30 year time period up to 2030. As identified in scenarios 7.5 to 7.7, to develop new technology to meet the 2006 and 2015 statutory targets for recycling and composting of household waste in the UK, the annual net unit cost will increase by approximately £20m between 2006 and 2015.

The chapter has highlighted limitations of EU waste policy identifying how the design of policy can create additional financial burdens on the opportunity for new technology. For example it identifies the weakness of setting targets for the recycling and recovery of waste. It identifies a non-linear increase in cost compared to increased recycling rates needed to comply to the statutory targets.

The chapter has highlighted the extent to which the financial, environmental and social drivers can create barriers to new technology by creating an additional financial burden on the opportunity for new technology. For example the chapter has shown that though Plastic diversion technology is more expensive to develop than composting, given the social objections to the development of new composting facilities in the Bedfordshire sub-region it is more favourable to adopt the higher financial cost plastic diversion technology.

The chapter has provided evidence to demonstrate that policy should not be designed so constrictively as it is at present. Policy needs to be designed with the ability to consider the range of technology drivers such as economic, environmental and social impacts and the consequences of interaction between these drivers. To stimulate technology innovation, or rather reduce the barriers to technology innovation, a more flexible approach to policy design and implementation is needed.

Chapter 2 identified limitations of previous waste management models such as their inability to allow variation to spatial resolution, varying system boundaries and the impact of uncertainty. Chapters 4 and 5 described how the model was designed to allow variation to these issues enabling the model to address the weakness of previous models. Chapter 8 shows how variation to these issues can affect the performance of waste strategy and the opportunity for new technology.

Chapter Eight – Modelling variation to the boundaries of the IWMS

8.1 Introduction

This chapter investigates the extent to which the design of the Integrated Waste Management System (IWMS) that results from EU waste policy and its implementation in the UK, affects the opportunity for new technology.

As identified in Chapter 1 factors such as the determination of spatial resolution, the boundaries of the system and uncertainty over time can affect the opportunity for new technology. For example through varying the boundaries of an IWMS, larger scale facilities might be developed at lower net unit cost as economies of scale and economies of production can be realised.

As identified in Chapter 2 a limitation of waste management models is their failure to consider variation of these key components of an IWMS and their impact on the opportunity for new technology. Chapter 4 described how these limitations were considered in the design of the model.

This chapter identifies how consideration of these variables affects the opportunity for new technology through identifying the costs associated with the development of different technology options. Through identifying the extent to which EU waste policy and its implementation in the UK allows or constrains such variation provides an assessment as to its impact on the opportunity for new technology.

8.2 Spatial Resolution Variation

As identified in earlier chapters the fragmented waste management structure in the UK can create 'artificial' spatial boundaries to the management of waste. Through varying the spatial resolution of technology assessment the extent to which these barriers affect system performance and opportunity for new technology can be determined. Variation to spatial resolution allows assessment of strategic waste management objectives/issues such as:

- The shifting policy towards regional waste strategy planning,
- The opportunity for economies of scale of technology,
- The opportunity for local authorities to collaborate to achieve recycling targets.

As identified in Chapter 4, section 4.2.1, to assess the cost of the spatial policy on system performance and opportunity for new technology variation between two spatial resolution levels is modelled:

(a) Bedfordshire Region
(b) East Anglia Region

8.2.1 Waste Generation in the East Anglia Region

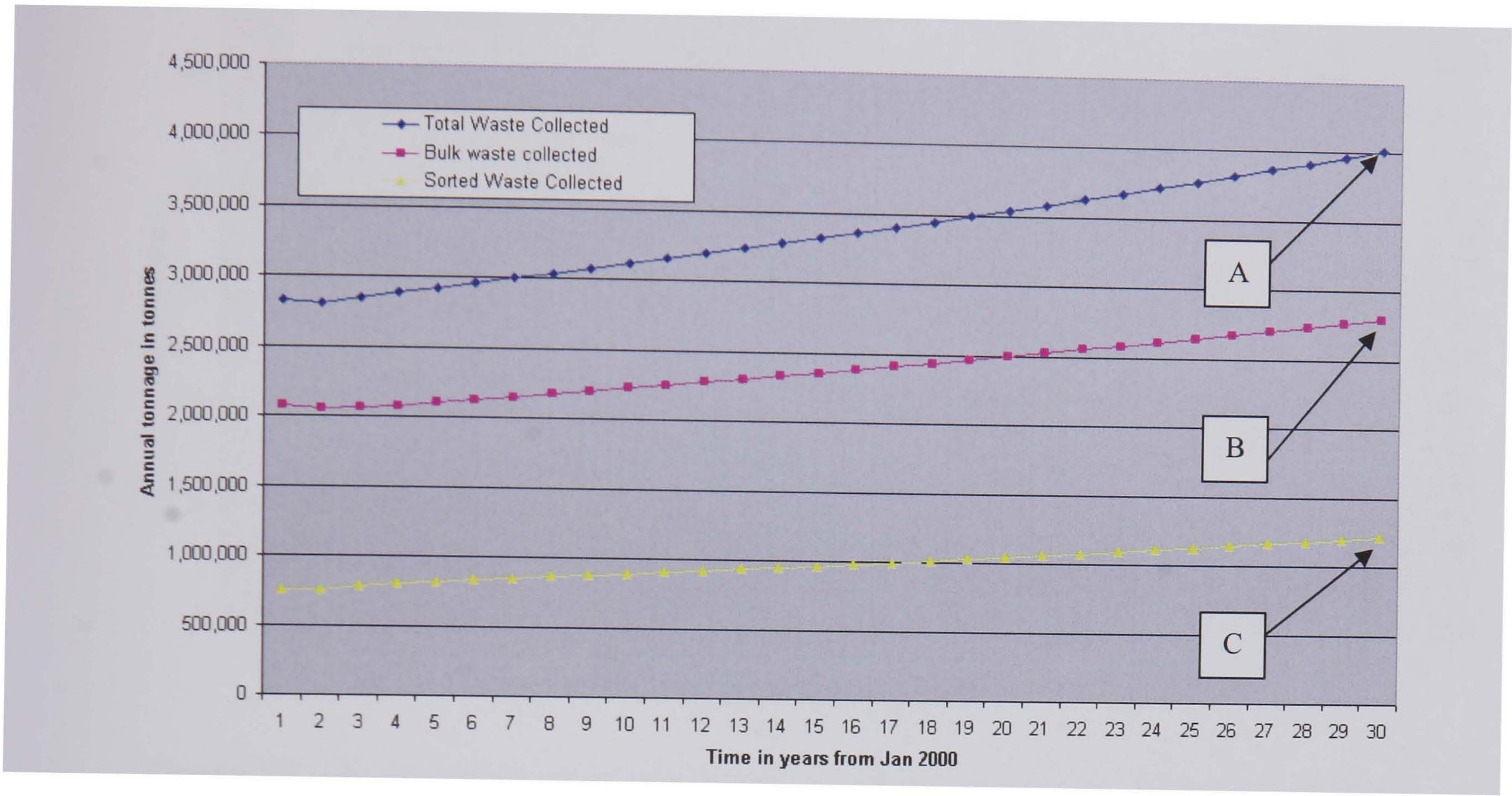


Figure 8.1 – East Anglia Region waste collected in tonnes per week

Figure 8.1 shows:
The waste throughputs for the East Anglia Region

- Point A – Total waste collected in the East Anglia Region, 4,014,286 tpa at 2030.
- Point B – Total unsorted waste collected, 2,799,553 tpa at 2030.
- Point C – Total sorted collected waste, 1,214,732 tpa at 2030.

To treat 100% of unsorted waste in 2030, facilities with a processing capacity of 2.8mtpa would be needed. This creates problems in comparing the results between modelling the Bedfordshire sub-region and the East Anglia region as the scale of waste process technologies such as EfW and MBT needing to be developed would be beyond the scale of facilities currently developed or operational. For example to meet a 2.8mtpa processing capacity by 2030, larger scale facilities such as 3*1mtpa facilities would need to be developed or 7*400ktpa EfW facilities (i.e. the maximum sized facilities considered in the Bedfordshire sub-region). Applying costs for such large-scale (unproven) facilities would be difficult to justify. Developing such larger scale facilities would be extremely problematic given the NIMBY attitude to waste management facilities as identified in Chapter 2, section 2.2. In this thesis it is assumed that the largest scale of EfW facility to be developed is a 400ktpa facility. Any development of larger scale facilities is determined through multiplication of smaller facilities. For example to achieve a 2.8mtpa facility 7*400ktpa facilities are developed.

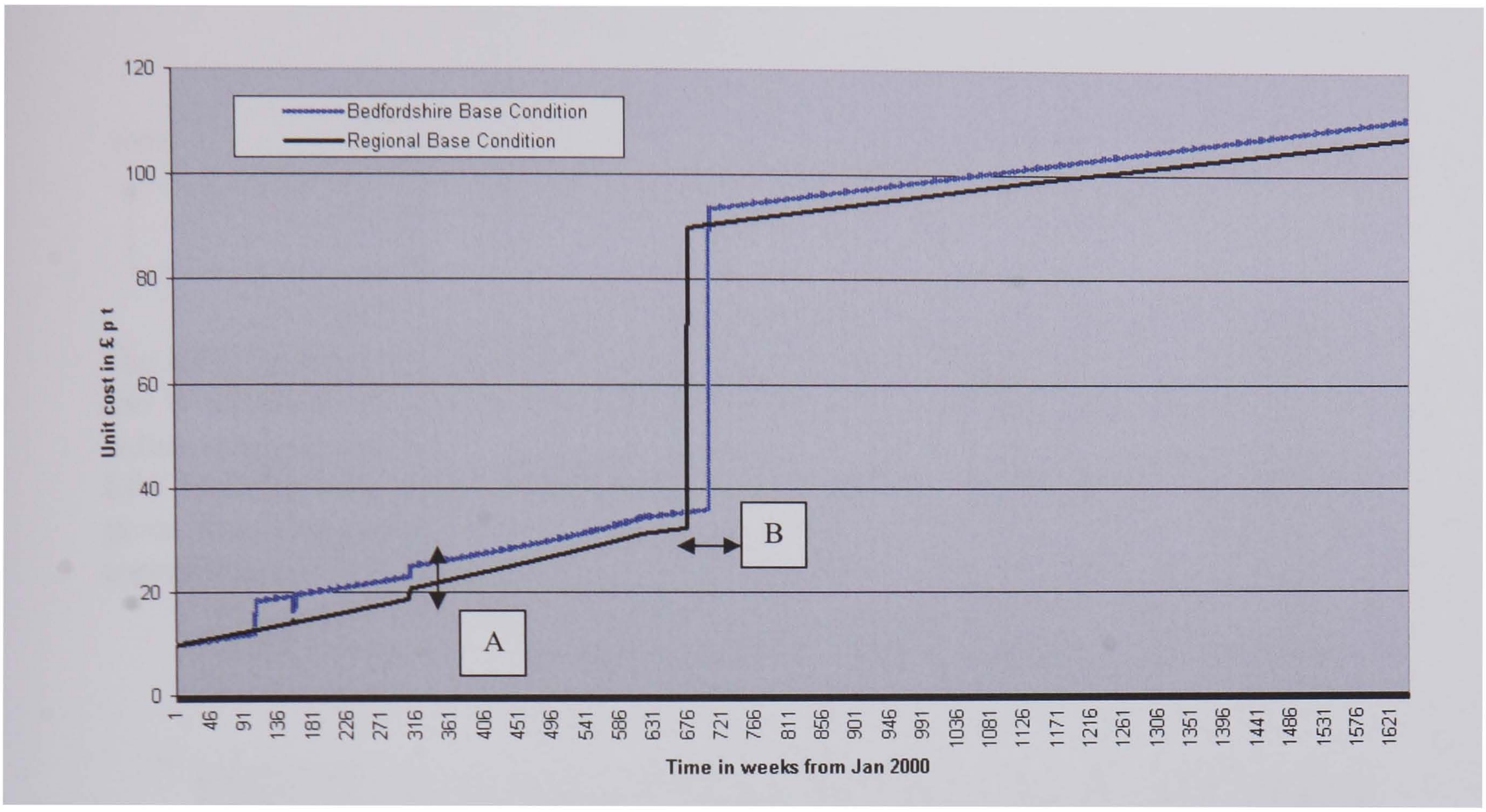


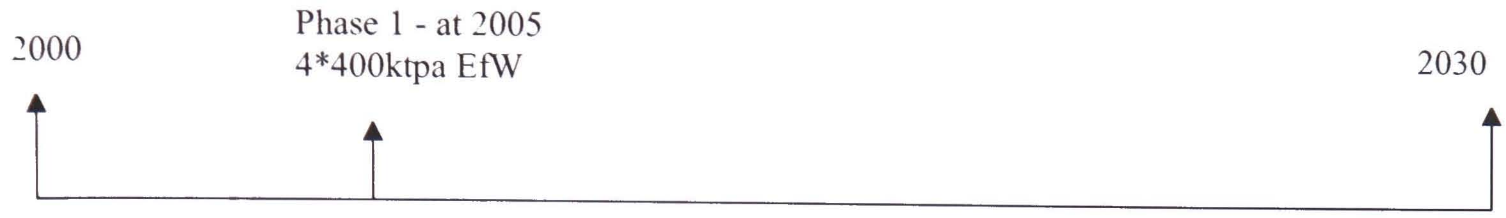
Figure 8.2 – Bedfordshire sub-region base condition and East Anglia region base condition, Real Operating Cost

Figure 8.2 shows:

- Point A – In the East Anglia region unit costs are lower by approximately £3 – 4pt. The cause of this variation could be due to the proportion of waste imported to the Bedfordshire sub-region being different to the East Anglia region (no conclusive reason has been identified).
- Point B – The landfill capacity is reached in the East Anglia region sooner than in the Bedfordshire sub-region by approximately 1 year, 2012 and 2013 respectively. This is due to the high proportion of landfills in the East Anglia region being located in the Bedfordshire sub-region.

Given that the East Anglia region landfill capacity is exceeded at approximately the same time as the Bedfordshire landfill capacity i.e. 2012 compared to 2013, the value of landfill as a resource could increase and become an increasingly valuable resource. Waste intended for landfill will have to be exported greater distances outside of the region, not just outside the sub-region of Bedfordshire. This identifies the importance of landfill as a resource to the private waste companies operating in the Bedfordshire sub-region and the East Anglia region.

Scenario 8.1 – Time horizon for the one phase technology change through the development of 4*400ktpa EfW facilities



The EfW facilities are located in each quadrant of the East Anglia region i.e. N, S, E and W. Transport Distances between waste facilities are calculated using the area and radius method identified in Chapter 5, section 5.3.5. The development of 4*400ktpa EfW facilities with varying rates of diversion of unsorted collected waste is modelled given that 2.7mtpa of waste is collected by 2030, i.e. it has the capacity to process approximately two thirds of the waste throughput.

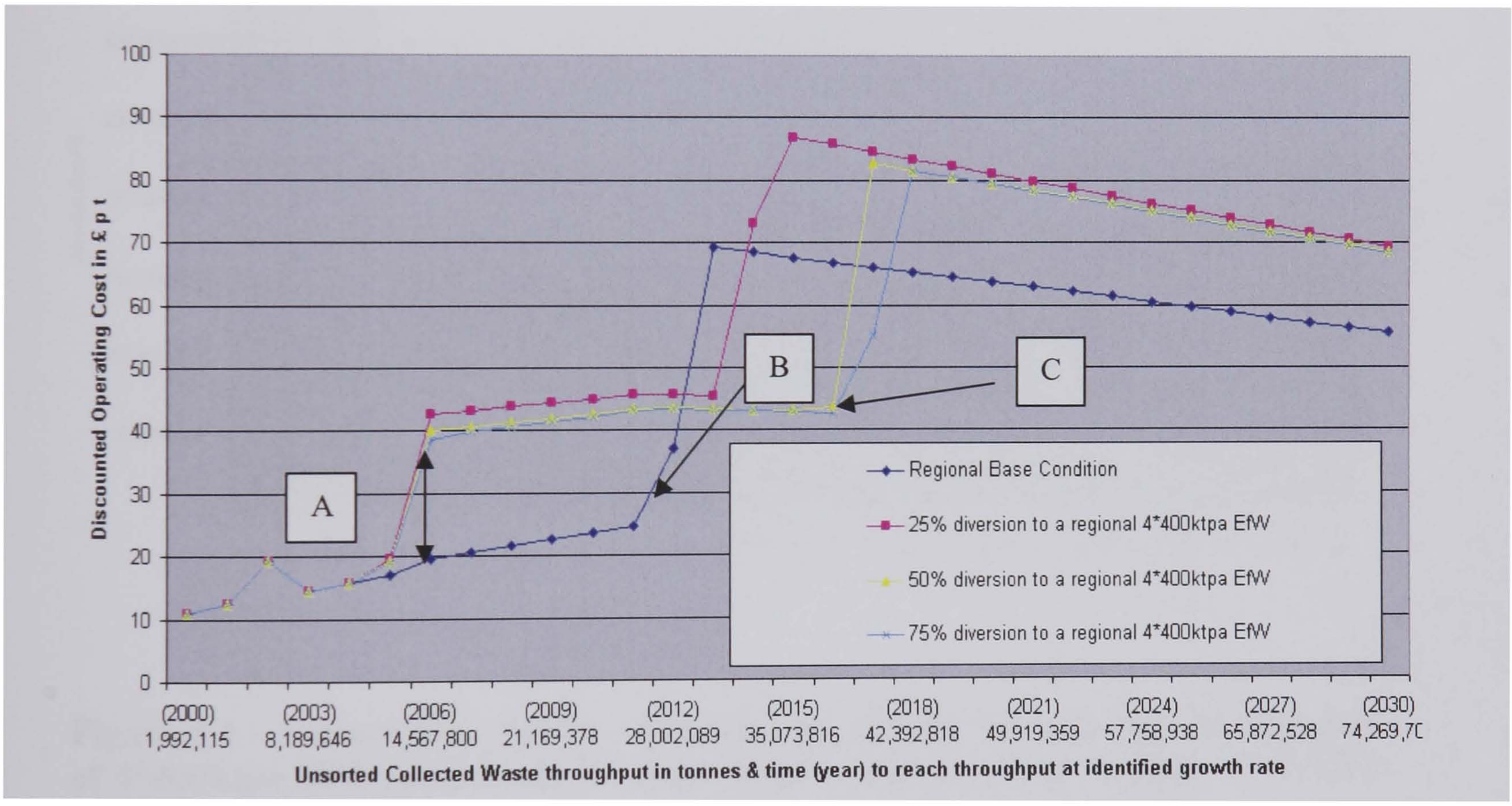


Figure 8.3 – Discounted operating cost for variation through the development in the East Anglia region of 4*400ktpa EfW facilities, net unit cost at 3.5% discount rate.

Figure 8.3 shows:

- The cumulative throughput of unsorted collected waste for the East Anglia region is significantly larger than for the Bedfordshire region only i.e. around 74m tonnes compared to 11m tonnes.
- Point A – The net unit costs for processing the unsorted collected waste increase by approximately £20pt i.e. from £20 pt in 2006 to £40 pt at 2003 values. This increase in costs is due to the additional transportation of waste within the four

regional quadrants of N, S, E, and W to the EfW facilities and the higher operating cost of EfW compared to landfill as described in Chapter 4.

- Point B - For the East Anglia region base condition the reaching of landfill capacity for the region is anticipated to be around 2012. Thus the landfill capacity for the region will be exceeded at roughly the same time as the landfill capacity for Bedfordshire sub-region and supports the importance of maintaining landfill capacity, as described earlier.
- Point C - Given the much larger sized facilities to be built the time before reaching landfill capacity is delayed significantly to around 2016 compared to 2012 for the base condition as waste intended for landfill is diverted to the EfW facilities. The greater the diversion rate from landfill to EfW i.e. 50% to 75% the greater the delay in reaching landfill capacity.

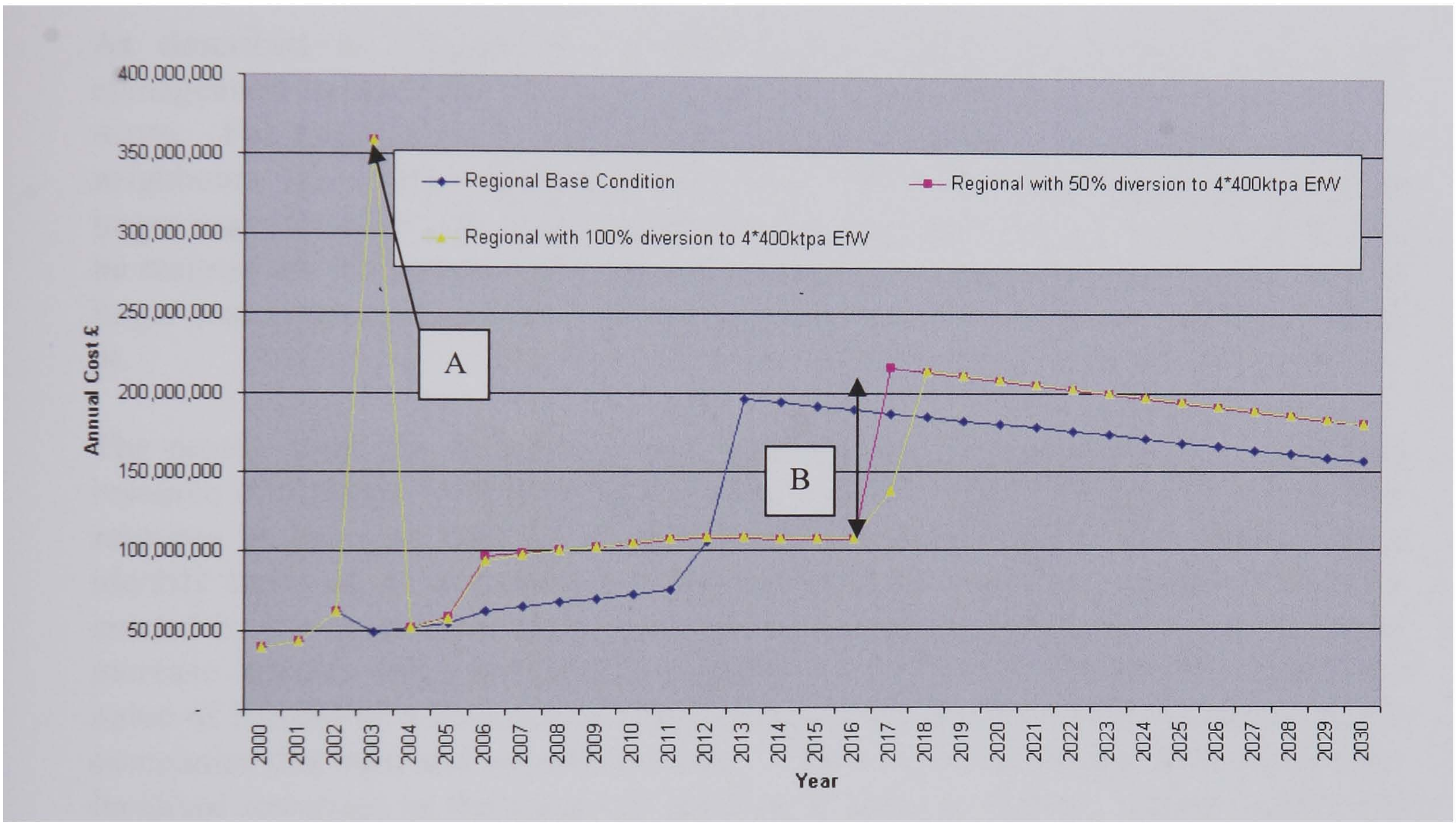


Figure 8.4 - Annual Cost Profile of technology change through the development of 4*400ktpa EfW facilities in the East Anglia region to treat unsorted collected waste at 3.5% discount rate

Figure 8.4 shows:
The annual costs are for the East Anglia region compared too the Bedfordshire sub-region, are considerably higher (as would be expected given the increased waste flows).

- Point A – The maximum annual cost if developing 4*400ktpa EfW facilities, is approximately £355m.
- Point B – After the capital investment in the EfW technology, net annual costs are approximately stable between 2006 and 2016 when landfill capacity is exceeded and costs rise. The costs are approximately £100m between this time period and rise to around £200m at 2017.

8.2.2 Analysis of variation to spatial resolution on technology performance

Given the similarity in the results between the Bedfordshire sub-region and the East Anglia base condition scenarios it is debatable as to the utility of the results for variation to spatial resolution. What might be occurring in the results is that simplification to support variation of spatial resolution has affected the utility of the results. In order to support variation between spatial resolution the model based upon the Bedfordshire sub-region is merely inputted with regional data, this reduced modelling time and was perceived as sufficient to achieve the modelling objectives. An alternative approach would be to develop a separate model in Simile to more closely simulate the East Anglia region, potentially causing a considerable increase in time for model development. The model is displaying a common deficiency of models (as identified in Chapter 5) in that simplification to assist model development has been at the detriment of the utility of the model.

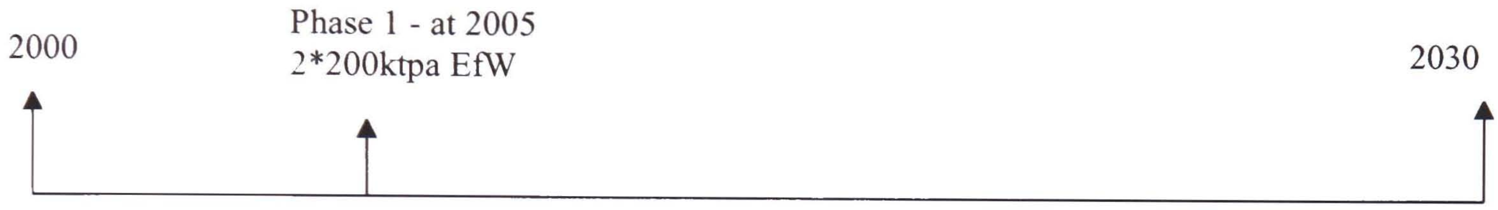
As described in Chapter 4 the fragmented management structure for waste management in the UK creates artificial spatial boundaries to the management of waste. For example local authorities are often reluctant to collaborate with their neighbours when developing waste strategy. The financial benefits of adopting larger scale facilities that enable economies of scale and economies of production to be realised are displayed in the results. Scenario 8.1 shows the benefits of adopting larger scale regional facilities with net unit operating cost reduced to around £40-42 pt.

The results show the importance and value of landfill as a resource. As landfill resource diminishes over time, as the only ultimate disposal option for waste, this resource is going to become an increasingly valuable asset. The model results identify the cost of transferring waste between the 'artificial' spatial boundaries created by the fragmented waste management system in the UK (as identified by the increase in costs when the landfill capacity is exceeded). The results identify the value of landfill of a resource to regions such as Bedfordshire and the private waste companies that own and operate the sites. They will be encouraged to preserve their localised resources as the asset will increase in value over time. Policy intended to reduce the use of landfill will in fact be rewarding owners of existing resources. This is as landfill is the only disposal technology for waste and all other treatment technologies still produce residues that require disposal to landfill. Thus there will always be a demand for landfill and by implying policy constraints on its use and development existing resources will become more valuable.

8.3 Shifting Boundary Assessment

As identified in Chapter 2 one limitation of waste management models is the difficulty of modelling variation to boundaries of the system. Within the Bedfordshire sub-region imported waste dwarfs waste generated in the sub-region. As identified in Chapter 5 around 5/6ktpw of MSW is produced in the sub-region compared to 60ktpw imported to Bedfordshire landfills. The results presented in this section investigate the impact of this imported waste on strategy performance. This highlights how defining the boundaries of the system within a waste management model can affect the system assessment.

Scenario 8.2 – Time horizon for the one phase technology change through the development of 2*200ktpa EfW facilities in the Bedfordshire sub-region with no consideration of the imported waste



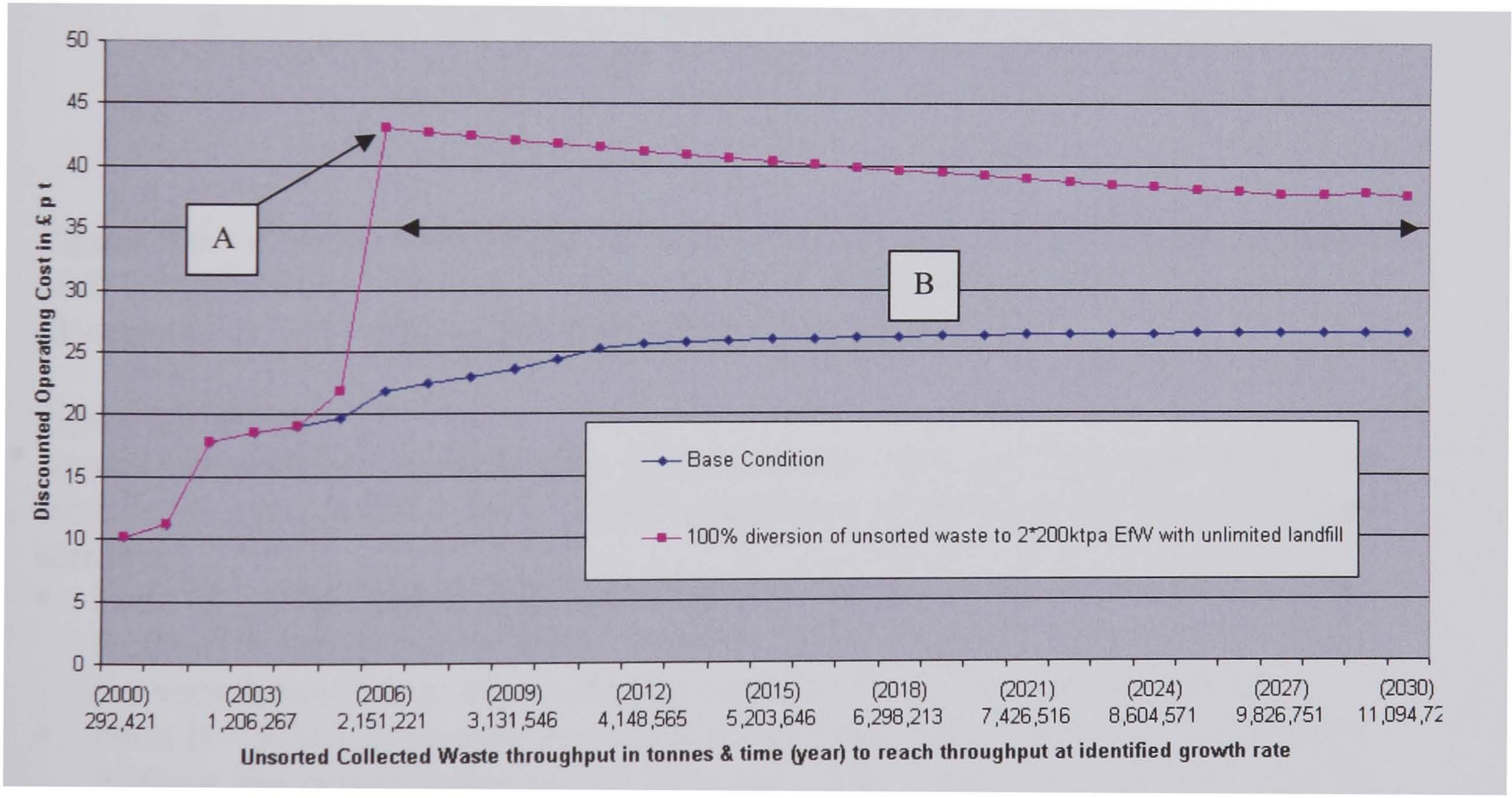


Figure 8.5 – Discounted operating cost at 3.5% for variation through 100% diversion of unsorted waste to 2*200ktpa EfW Bedfordshire with unlimited landfill capacity, discount rate at 3.5% to 2003 values

Figure 8.5 shows:

- Point A – Without the consideration of the imported waste to the Bedfordshire sub-region landfills the net unit operating cost for the 2*200ktpa EfW facilities is approximately £44pt at 2006.
- Point B – The net unit operating cost decreases over the 30year time period though costs appear more stable than when imported waste is considered.

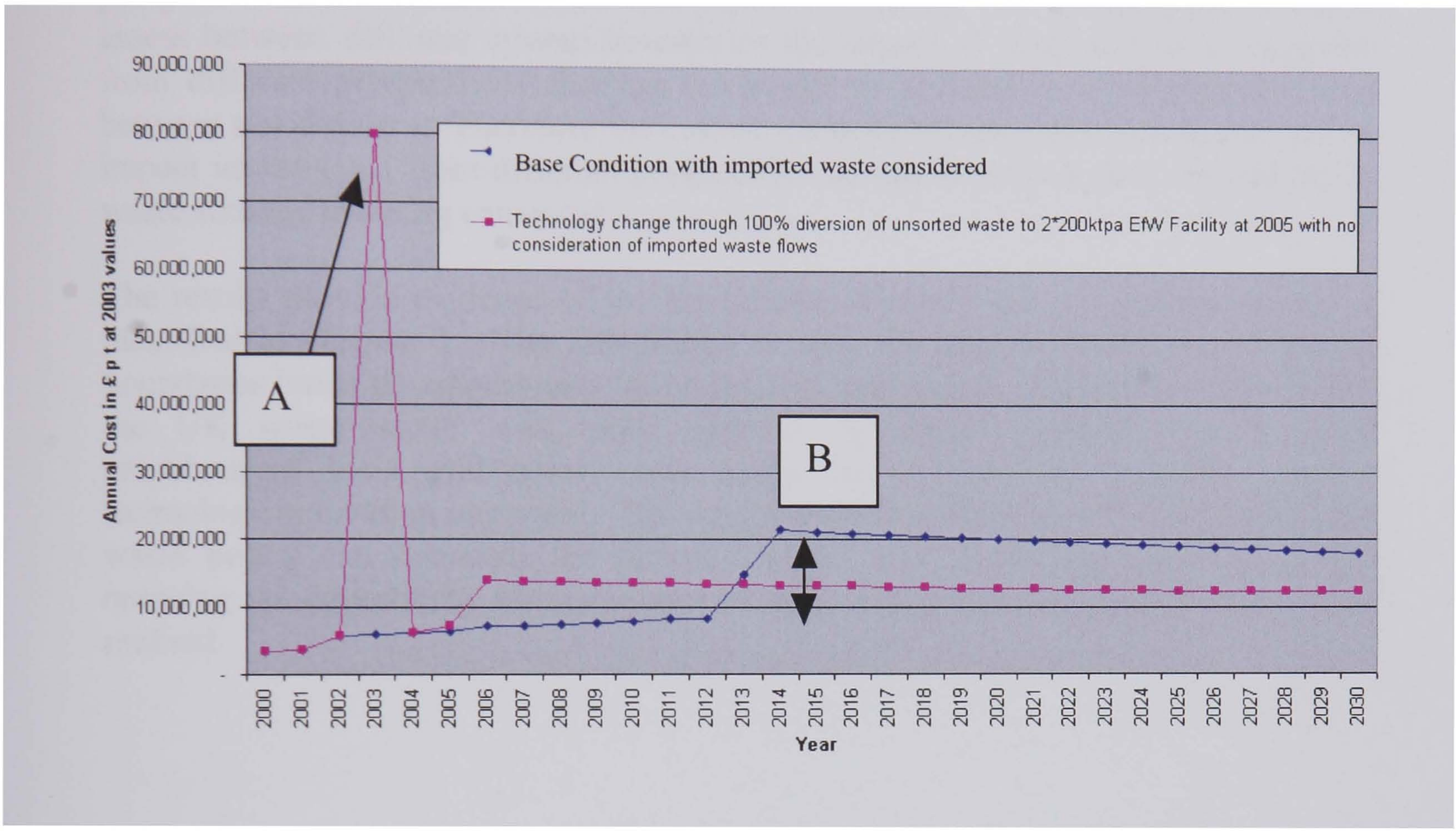


Figure 8.6 – Annual Cost Profile of technology change through the development of 2*200ktpa EfW Pyrolysis facilities to treat 100% of unsorted collected waste discounted at 3.5% with no consideration of imported waste

Figure 8.6 shows:

Annual net costs are lower around £14m between 2006 and 2030 and there is no increase in costs at 2014 when landfill capacity is exceeded in the Base condition scenario.

- Point A – The annual cost in the year of investment in the 2*200ktpa EfW facilities is approximately £80m. As identified in Chapter 7 the timing of this cost can vary depending on the accounting practice of the private waste company.
- Point B – When comparing the results a significant variation in costs is identified. Without the consideration of the imported waste annual costs are less than the base condition costs.

8.3.1 Analysis of Shifting Boundaries on System Performance

The results show the impact of varying the boundaries of the system on the assessment of strategy performance and costs. It justifies the importance of designing the model to allow variation to the system boundaries as depending on the defining of the boundaries of the system the costs vary significantly. This is important aspect of the design of the waste management model as in the UK waste industry the delineation of boundaries of the system of assessment would depend on the perspective of the decision-maker and policy constraints. By enabling the model to assess between different system boundaries the impact of costs can be investigated from different perspectives allowing the model to be used as a collaboration tool between stakeholders. Therefore the cost of waste policy can be demonstrated and its impact investigated from different perspectives so that improved decision-making in waste strategy planning can occur.

The results provide evidence of the limitations of policy and its implementation as identified in Chapter 1. The inflexibility to vary the spatial resolution and system boundaries limits the opportunity for technology innovation. The results show that if the UK waste sector was more adaptive to support collaboration between neighbouring local authorities costs could be reduced and opportunities for technology innovation improved. The results show that the proximity principle of EU waste policy can constrain the opportunity for new technology options through reducing the opportunity for economies of scale and economies of production to be realised.

8.4 Environment Uncertainty

In Chapters 4 and 5 it was identified the need to consider uncertainty in the design of model. This is identified as an important consideration on opportunity for technology given the variation in types of uncertainty and the impact of uncertainty over time on technology performance.

In the UK waste industry, as described in Chapter 4, there is uncertainty over many key operational variables such as waste composition, waste generation, recycled market prices and transport costs. As highlighted in Chapter 2, Table 2.2, this uncertainty creates a barrier to long-term planning.

The impact of uncertainty on the performance and cost of paper recycling technology is modelled and investigated. Uncertainty affects many issues relating to the performance of paper recycling from market prices, transport costs, waste composition and the legislative targets etc. As described in Chapter 2, the WRAP 'Paper Recycling Report' (2002) identifies the key obstacle to increased paper recycling as the uncertainty over the marketability of the recycled product. This entails uncertainty surrounding the location of markets, the value of recycled material, the extent of future markets and varying waste composition over time.

As described in Chapter 4, waste paper in the Bedfordshire sub-region collected for recycling through the household source separation schemes i.e. the Blue box and the Orange sack schemes, is further sorted and packaged at the MRF's before transfer to the Shotton paper mill, Chester (see Table 4.2). If paper recycling is to help attain the growing legislative targets for recycling as identified in Chapter 1, new markets are needed as paper recycling grows in the UK and the market becomes saturated.

Paper recycling within this thesis is viewed as potentially a multiple phase new technology opportunity. For example the decision to adopt paper recycling for further markets in the UK can be viewed as a one phase technology change event, paper recycling to both the UK and European markets can be viewed as a two phased technology change.

Different scenarios are modelled to assess the impact of paper market uncertainty on system performance. These include:

- Variation to market price
- Variation to distance to market
- Variation to waste composition over time

Scenario 8.3 - Variation to Paper Market Price

Variation to paper market price helps identify the extent to which uncertainty in market price affects technology performance through recycling. Table 2.1 (Chapter 2) shows the uncertainty and variation associated with paper material recycling prices over only a short time period of 3 years compared to the 30 year time period that will be modelled. Variation between random and fixed values is modelled as it helps to address the different types of uncertainty such as dramatic events, emergence or surprise as identified in Chapter 4, section 4.2.4.

The scenarios modelled to simulate uncertainty of paper market price include:

- Base Conditions with Paper market price random variation between £0-100 pt
- BC with paper market prices reduced by 50% of base condition prices
- BC with paper market prices increased by 100% of base condition prices

The modelling is intended to identify the limits of technology performance therefore large ranges in variation of key variables such as 150% variation or 300% variation are modelled. It could be argued that rather than identify £0 as the minimum value of recycled paper when the market becomes saturated it should display a negative value as the paper still needs disposal. In the model if the paper market price is £0, the model is designed to reject the paper for recycling purposes and transfer the paper to landfill, therefore the cost of landfill is still considered in the net unit cost of the scenario.

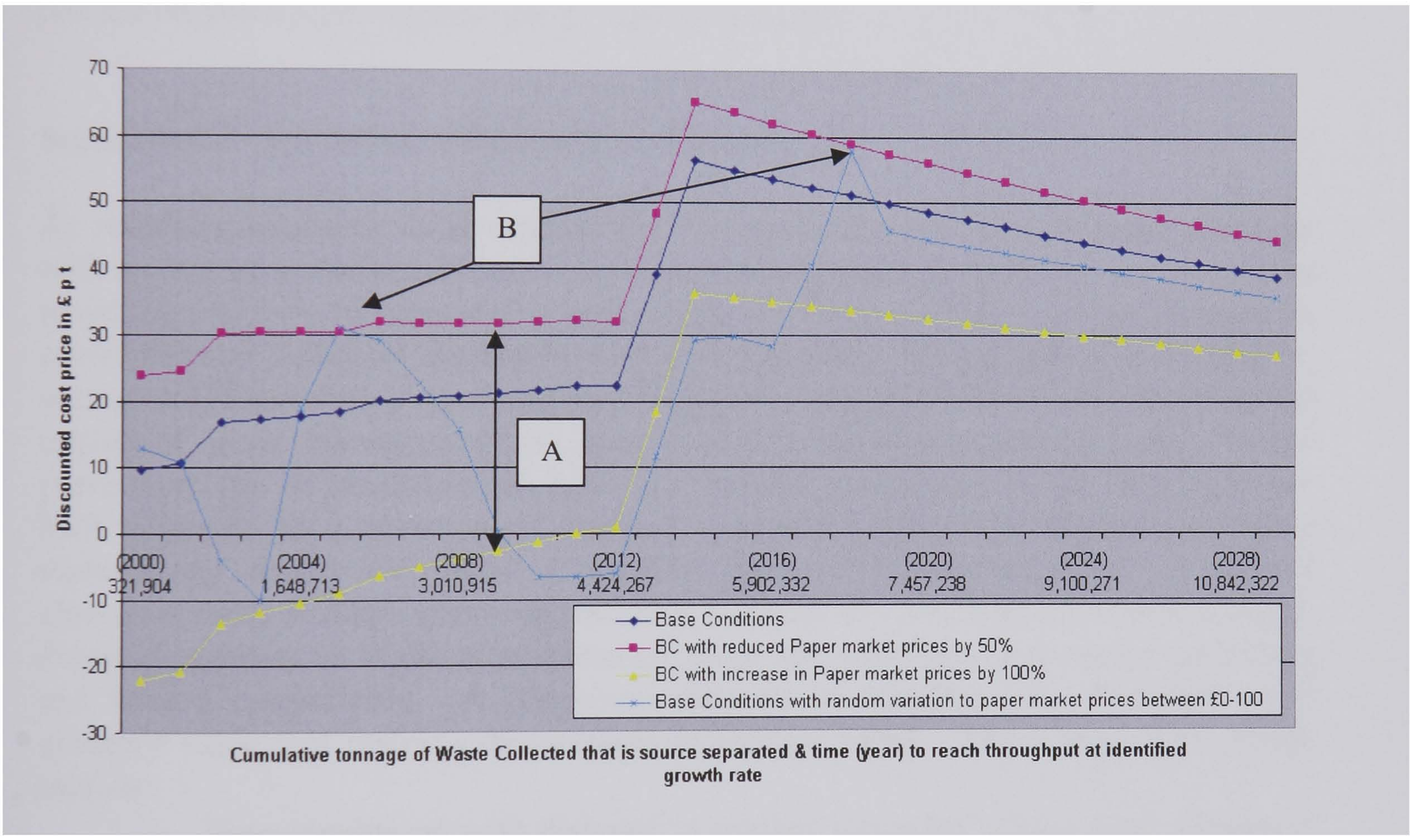


Figure 8.7 – Discounted operating cost of variation to Paper Market Price on technology performance at 3.5% discount rate

Figure 8.7 shows:

- Point A - The net unit cost is affected by the variation of a single uncertain variable within the system. For example the net unit cost range is approximately £35 pt at 2009 (at 2003 values) between a 50% reduction in paper market price and a 100% increase in paper market price.
- Point B – The net unit cost varies as the market price for recycled paper is randomly varied between £0 and £100 pt. The graph shows that when paper market price is £0 i.e. there is no market for recycled paper, technology cost

reaches a maximum e.g. £32 pt at 2005 and £60 at 2018 (at 2003 values). The other deviations in unit operating cost reflect the events identified in Chapter 6.

- The graph shows the susceptibility of paper recycling to paper market price.

As described in Chapter 1, waste legislation is creating increasing recycling targets. Waste strategy in the UK (as defined by the 'Waste Strategy 2000' (Defra, 2000a) report) describes the development of the Waste Recycling Action Program with a focus on individual waste material strategy to achieve the legislative targets. The results show the sensitivity of adopting a single waste material strategy (or one phase technology) versus a multiple waste material strategy (or multiple phase technology). The example shows that sensitivity of adopting one phase technology approach given the uncertainty associated with a single key variable such as market price for recycled paper. Through reducing the flexibility of strategy from the aggregation of sequences of technology change (multiple waste materials) to one phase technology change (single waste material) technology performance is more sensitive to uncertainty.

Further investigation is needed to assess whether system performance is sensitive to just the recycled paper market price or other variables.

Scenario 8.4 - Variation of Distance to Market

As recycling increases local markets for recovered materials will become saturated with recovered material needing to be transported to markets further away. Increased recycling can lead to increased transportation of waste and the resultant increase in environmental pollution associated with transportation. As suggested in Chapter 1, section 1.2, legislation to promote recycling and aimed at reducing the environmental impact of waste management can merely transfer the environmental costs. Waste paper from the Bedfordshire sub-region is currently transferred to the Shotton Paper Mill, Chester, at a distance of 256km. Stepped changes in distance to paper reprocessing facility are modelled to reflect potential markets locations. A stepped change is more realistic given the fact that markets are not homogeneously located. Potential markets in Western or Eastern Europe are modelled at distances of 625km and 968km respectively. A maximum distance of 1000km was identified as an arbitrary value that restricts the markets to Europe based. The scenarios modelled include:

- Base conditions with distance to market for paper reduce from 256km to 10km.
- Base conditions with stepped changes in distance to paper market to 625km and to 968km at 2010 and 2020.
- Base conditions with gradual variation in distance to paper market from 256km to 1000km over the 30 year time period.

The timings of the stepped changes were selected randomly. The main aim of modelling these scenarios is to demonstrate the impact of distance to new market on the system performance and costs.

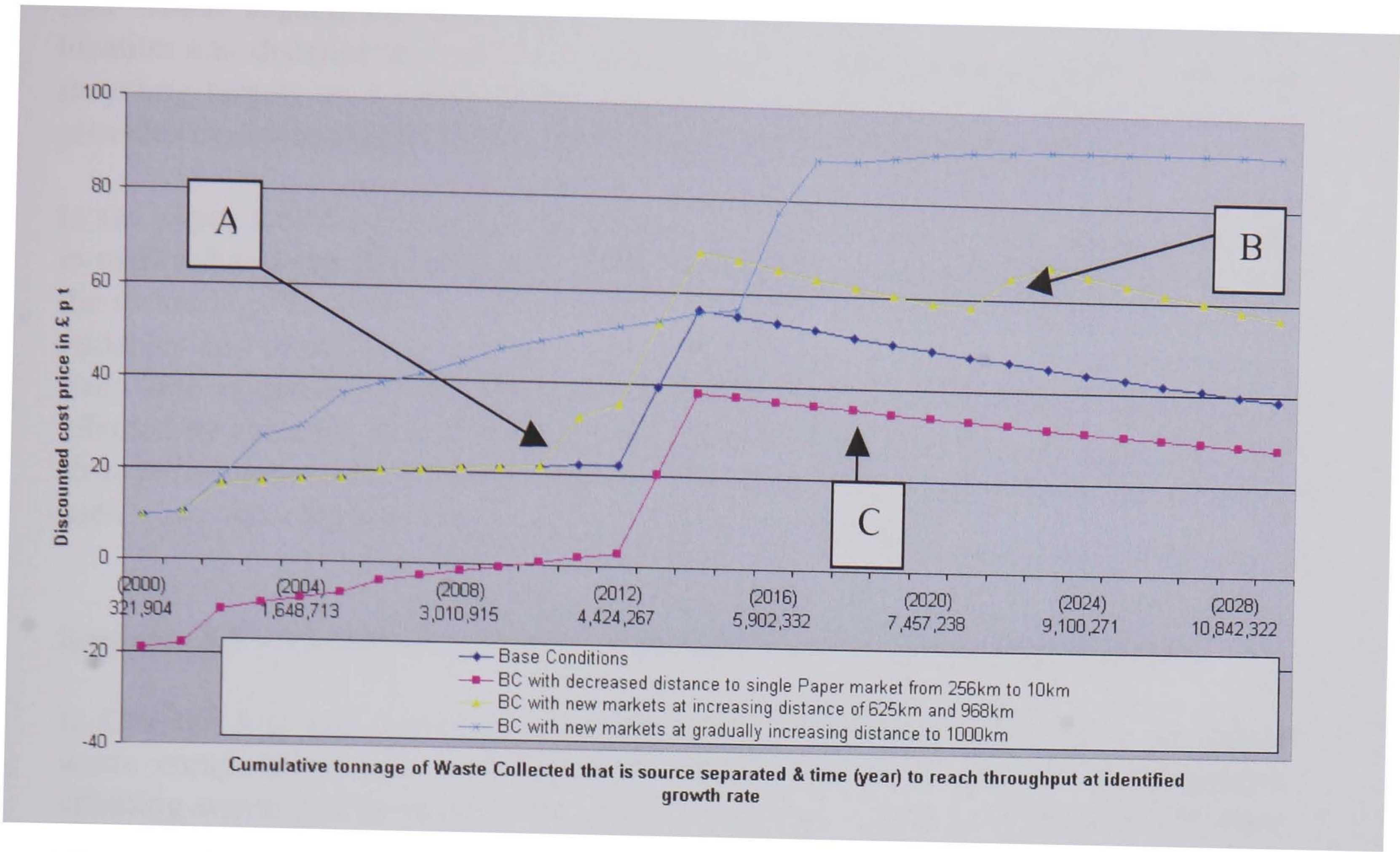


Figure 8.8 – Discounted operating cost of variation of Distance to Market on Technology Performance at 3.5% discount rate

Figure 8.8 shows:

- Points A + B - The yellow curve displays the impact of adopting a stepped distance to market. This demonstrates a two phased technology change approach. The timing of the step changes in distance to market are identified by the step increases in the net unit cost (Points A and B).
  - Point A shows that if distance to market is changed to western Europe the net unit cost of paper recycling will increase from £21 to £34 at 2011 (at 2003 values).
  - Point B shows that if two new markets are needed for the recycled paper i.e. Western and Eastern Europe the net unit cost increases from £44 to £63 at 2022 (at 2003 values).

  The step changes in cost at 2010 and 2021 mark potential limits of opportunity for paper recycling. As the step increases in cost might make recycling of paper uneconomical.
- Point C – The pink curve displays the impact of locating a paper mill at the MRF, therefore the paper is reprocessed as part of the recycling technology. The scenario displays reduced net unit costs at 2018, £37 compare to £52 for the base condition.

The scenario shows the sensitivity of distance to market on the system cost with costs increasing as distance to market increases. This type of analysis is useful in determining the maximum distance to market for paper recycling. For example as identified in the stepped distance to market scenario, if a maximum cost of £60 pt was assumed, the one phase technology change scenario of recycling paper for the Western European market would be justified. Two phased technology change, with transportation to the Eastern European market would not be justified, as the operating cost would exceed the maximum net unit cost. Given the uncertainty over the location and distance to market the scenario shows that developing strategy to attain recycling targets on a single waste material is sensitive to a key single variable. It provides evidence that this is a weakness of policy as identified in Chapter 1.

In the paper recycling scenario uncertainty associated with the key variable distance to market has a significant impact on the technology performance. Therefore though the technology is perceived as low risk, it is highly susceptible to uncertainty of key variables and therefore its ability to sustain performance in an uncertain environment over time is questionable. Through identifying the extent to which technology is affected by variation to key variables through modelling, decisions to assess the long-term performance of technology can be better informed. This information could be used when securing long-term contracts for the recycled paper.

Scenario 8.5 – Variation to waste composition on technology performance

In Chapter 3 it was described how Tukker et al., (2003) forecasts how household waste composition will vary by 2020. They identify 4 trends or developments affecting waste composition as society and attitudes evolve over the next 20 years. These scenarios identify how uncertainty could affect waste composition.

Four scenarios of potential future society were identified (described in greater detail in Chapter 3, section 3.2):

a) 'Media@home' (M@H) – a consuming culture with electronics dominating the household, with work, schooling, socialising and shopping all conducted on the electronic highway from home.

b) 'On the Road' (OTR) – people want flexibility as social interaction and fun are highly valued. Multifunctional, light and portable products are created to support a society that is continually on the move. With society fashion conscious a disposable society is created with products developed with short-lifespans.

c) 'Comfort community' (CC) - emphasis is on social values instead of possession of products, more of a communal community where services/products are provided and shared within a community.

d) 'Home sweet home' (HSH) - emphasis on living in the moment, people appreciate good quality products that last and are reliable with a demateralised society.

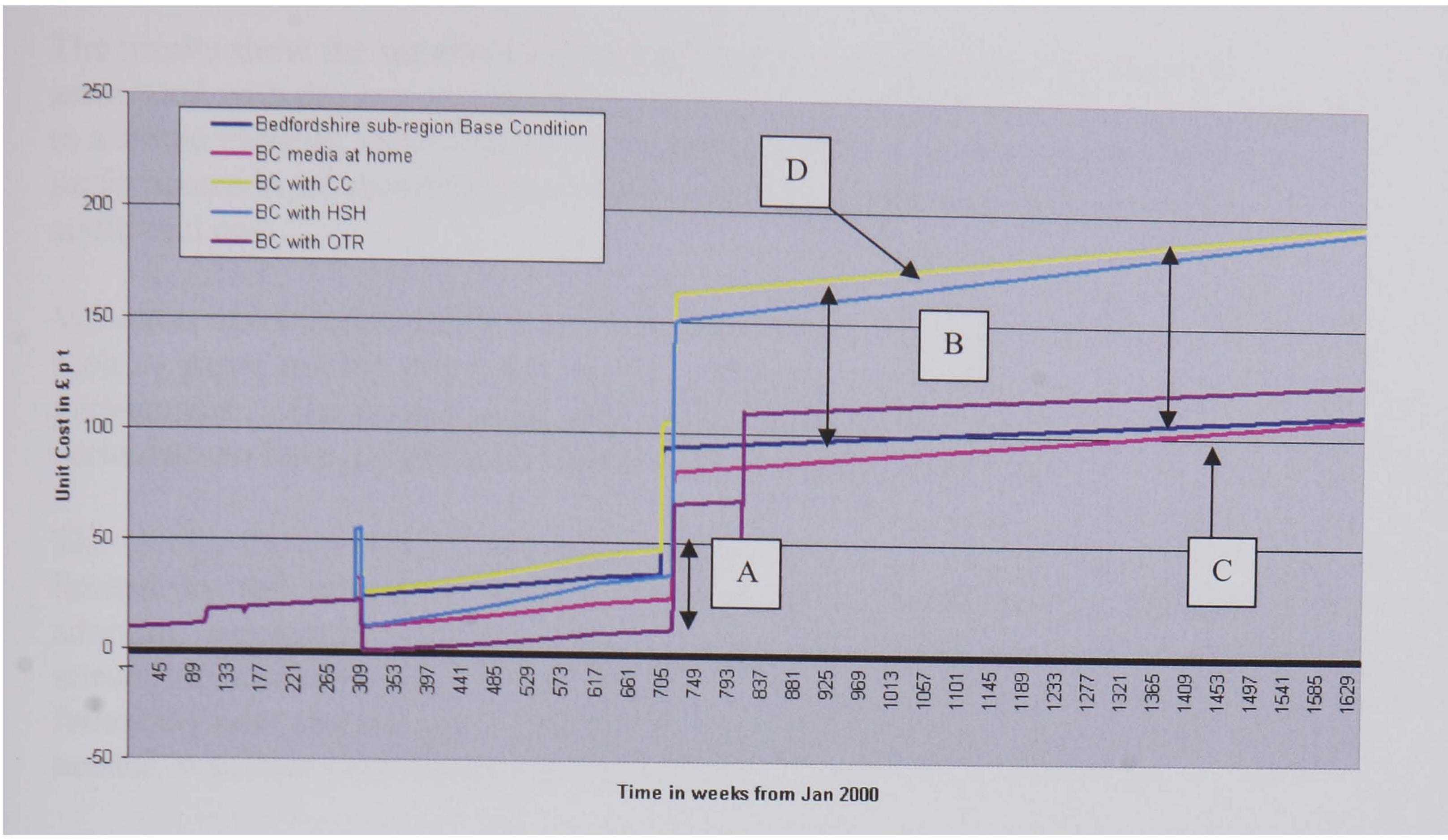


Figure 8.9 – Operating cost of variation to base condition and waste composition at real cost not discounted

Figure 8.9 shows:

- Point A – The range in the net unit cost of the base condition of approximately £40 pt at 2014, between the waste composition scenarios is identified. Therefore by maintaining the base condition scenario over the time period of assessment variation to a single variable such as waste composition can have significant impact on the technology performance.
- Point B – The variation in the impact of varying waste composition over time is displayed to increase over time. This is as the variation in waste composition is modelled as a gradual technology change over time and not a dramatic or singular timed event. As described by Tukker et al (2003) the variation in waste composition will occur in response to varying economic and social conditions over time.
- Point C - The 'Media at home' scenario will have the most financially beneficial impact on operating cost lowering costs by approximately £1-£10 over the time period of assessment. The media at home scenario is associated with a significant increase in the proportion of paper waste generated (see Table 4.2, Chapter 4), through the established paper recycling strategy the lowering costs could be explained by the increased recycling fraction and the revenue generated. The performance of this strategy would be dependent on the sustaining of markets for the recycled paper over time.
- Point D – The 'Comfort in the Community' scenario will have the highest increase on operating costs, increasing costs by up to £90 pt in 2020. The scenario is based upon the development of a communal community where emphasis is based upon community values rather than the possession of products. The scenario is associated with a significant increase in the proportion of other waste therefore this uncertainty over the unknown is creating additional costs as it is assumed to be bulky waste in the model.

The results show the sensitivity of technology performance due to uncertainty associated with the key operational variable waste composition. Given this sensitivity to a single variable, flexibility of technology is needed if technology is to sustain performance in an uncertain environment over time. But flexibility comes at additional cost.

Variation due to uncertainty over time has shown the sensitivity of a single variable such as paper market price, distance to market or waste composition on technology performance. The results show that the variation of any one of these single system variables can have a significant effect on the overall strategy cost.

The results show evidence to support the assessment in Chapter 1 that EU policy is limited by the setting of single waste stream or waste material objectives. By adopting a restrictive approach to policy design, technology is more sensitive to uncertainty and the sector is less likely to be innovative given the greater potential for failure of new technology. Greater flexibility in EU policy and strategy design is needed to sustain performance in an uncertain environment over time.

Chapter 1 identified that barriers to technology occur due to the conflict of interest between rapidly changing legislative demands and the need for stability to establish a long-term strategy to limit the uncertainty and risk associated with technology over time. To reduce the impact of uncertainty one approach is to establish fixed contracts for the recovery and recycling of waste streams. But if long-term contracts are established, flexibility to react to other components affected by environmental uncertainty, such as legislative targets, is reduced.

8.4.1 To what extent do the different types of environment uncertainty have on strategy performance and costs?

The identification of the most influential and sensitive variable are inconclusive. It is difficult to justify and identify the determination of a single variable most susceptible to uncertainty and influential on strategy cost given the variance in types of uncertainty described in Chapter 4, section 4.2.4. Uncertainty and variation to waste composition will be gradual, emerging and evolving events over time. Market prices might fluctuate in a surprising manner given their uncertainty over the last 30 years. By merely modelling a range of variable values to plus or minus 100% is insufficient, as it fails to address these issues of uncertainty as a variety of dramatic, emerging or surprise events. In reality as the type of uncertainty varies the response and results will vary e.g. if the event is a dramatic event like a war, strategy might be maintained at a temporary loss as the system is anticipated to return to its previous state once the war has ended. Equally if the uncertainty emerges over time such as with waste composition variation, technology will gradually evolve in response to this variation. Through increasing the aggregation of sequences of technology change, the flexibility of technology is improved and the ability of technology to sustain performance in an uncertain environment is improved.

8.5 Summary

The chapter has shown how EU waste policy and its implementation constricts the development of an IWMS that in turn affects the opportunity to vary key system components that can affect the system's performance and the opportunity for technology innovation. EU policy needs to be designed and implemented to stimulate technology innovation through encouraging the development of technology that is enhanced with characteristics to sustain performance in an uncertain environment over time. (This is discussed further in Chapter 10 with technology displaying the characteristics of Flexibility, Adaptability and Resilience sought).

The chapter has shown how technology assessment techniques need to consider the spatial resolution, system boundaries and uncertainty issues within their design as these issues affect the opportunity for technology innovation.

Chapters 7 and 8 have identified relationships between the cost of waste policy and the opportunity for new technology. A limitation of the annual cost profiles in Chapters 7 and 8 is that the capital costs are included as single points in time. An alternative calculation process is used in Chapter 9 to distribute these costs over the lifetime of the technology. This process is called the Annual Average Equivalent Value. The AAEV calculation is used to investigate the extent to which the process of innovation needs to be considered in the technology assessment technique.

Chapter Nine – Modelling Variation to the Costing Process

9.1 Introduction

As identified in Chapter 2, a limitation of waste management models is identified by the varying techniques of assessment i.e. Cost Benefit Analysis, Lifecycle Analysis or Multi Criteria Analysis. In this thesis a Cost Benefit approach has been adopted, but there are numerous techniques for assessing cost benefit i.e. optimisation tools, net present value etc. In this chapter a different evaluation technique is used to assess the extent to which the selection of assessment technique influences the cost results.

The Annual Average Equivalent Value (AAEV) is used to distribute the cost of new technology over the lifetime of the technology rather than apply the capital costs at a single point in time as in Chapters 7 and 8. Through the AAEV results the relationships between strategy costs and the rate and process of implementation of technology can be investigated. This provides further understanding of how the process of innovation needs to be considered.

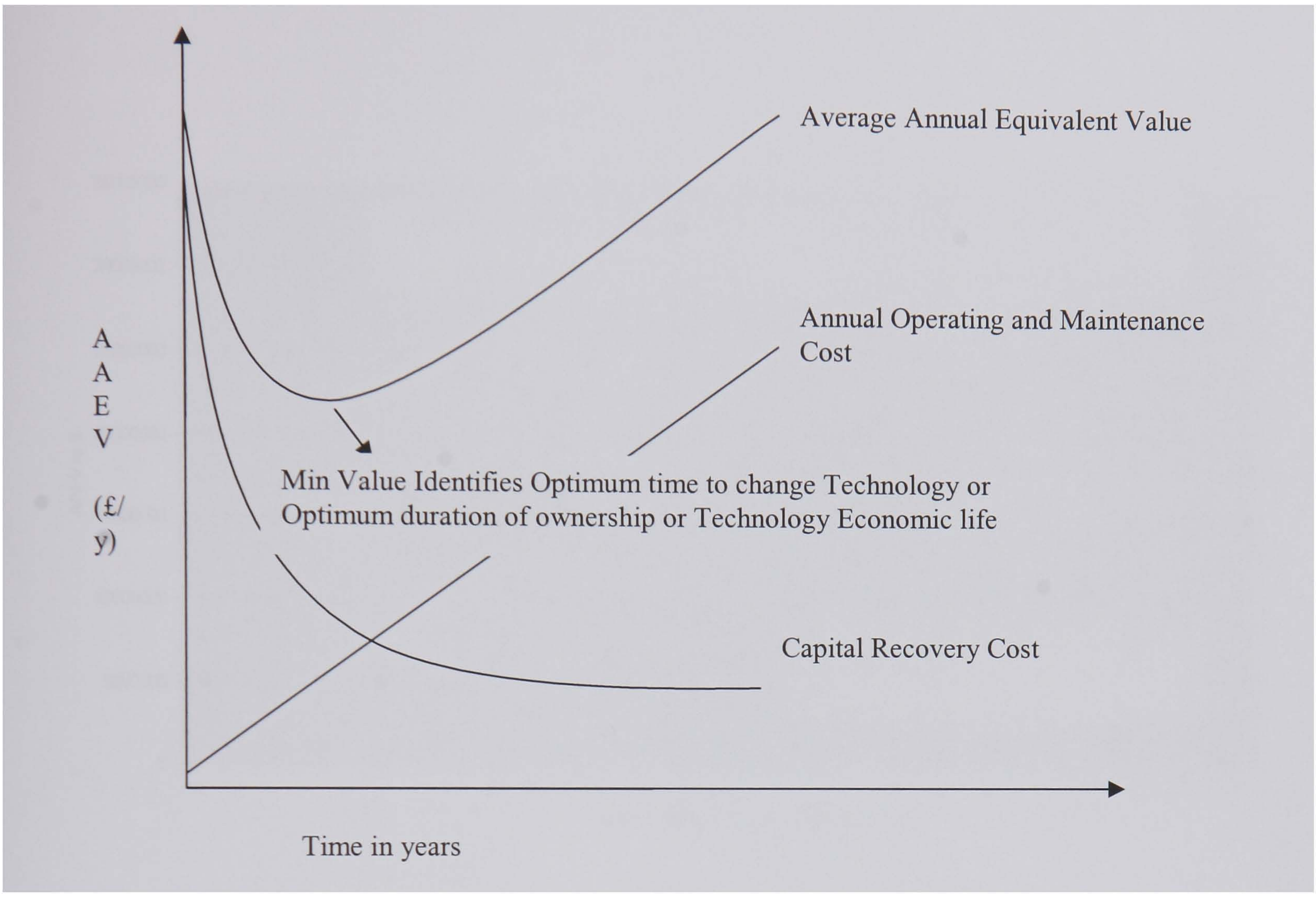
9.2 Annual Average Equivalent Value

AAEV supports comparative assessment of different technology options over time. It was adapted from Susamms (1973). The aim of the calculating process is to step through the successive years of ownership until a minimum AAEV is obtained. This time period is the optimum duration of ownership or the minimum discounted cost of owning and operating the asset. Figure 9.1 identifies the components used to calculate the Annual Average Equivalent Value.

The gradient of the curve provides an evaluation of the extent to which the duration of ownership of the technology is sensitive to uncertainty over time. Steep gradient curves identify dramatic changes in value of the technology and identify technology more sensitive to duration of ownership. Curves that show a lower gradient show less increase in technology costs and a greater 'insensitivity' to duration of ownership.

AAEV has been applied to a variety of technology assessment programs in recent years. Stephenson et al. (1998) used AAEV to assess the design and development of water recycling technology for sustainable cities. DOER (2002) used AAEV to assess engineering technologies for the recovery of dredged material from disposal facilities. U.S. Army Corps of Engineers (1999) used AAEV to assess technology variation on Salmon farming. The term 'Equivalent Uniform Annual Costs' (EUAC) is a more widely recognised variation of AAEV (White et al., 1987). These applications of AAEV have tended to concentrate on the evaluation of one off choice between two or more technologies. This chapter will use the AAEV method to assess the opportunity for sequences of technology investment.

Figure 9.1 - The portrayal of components for the identification of AAEV (Adapted from White et al., 1989)



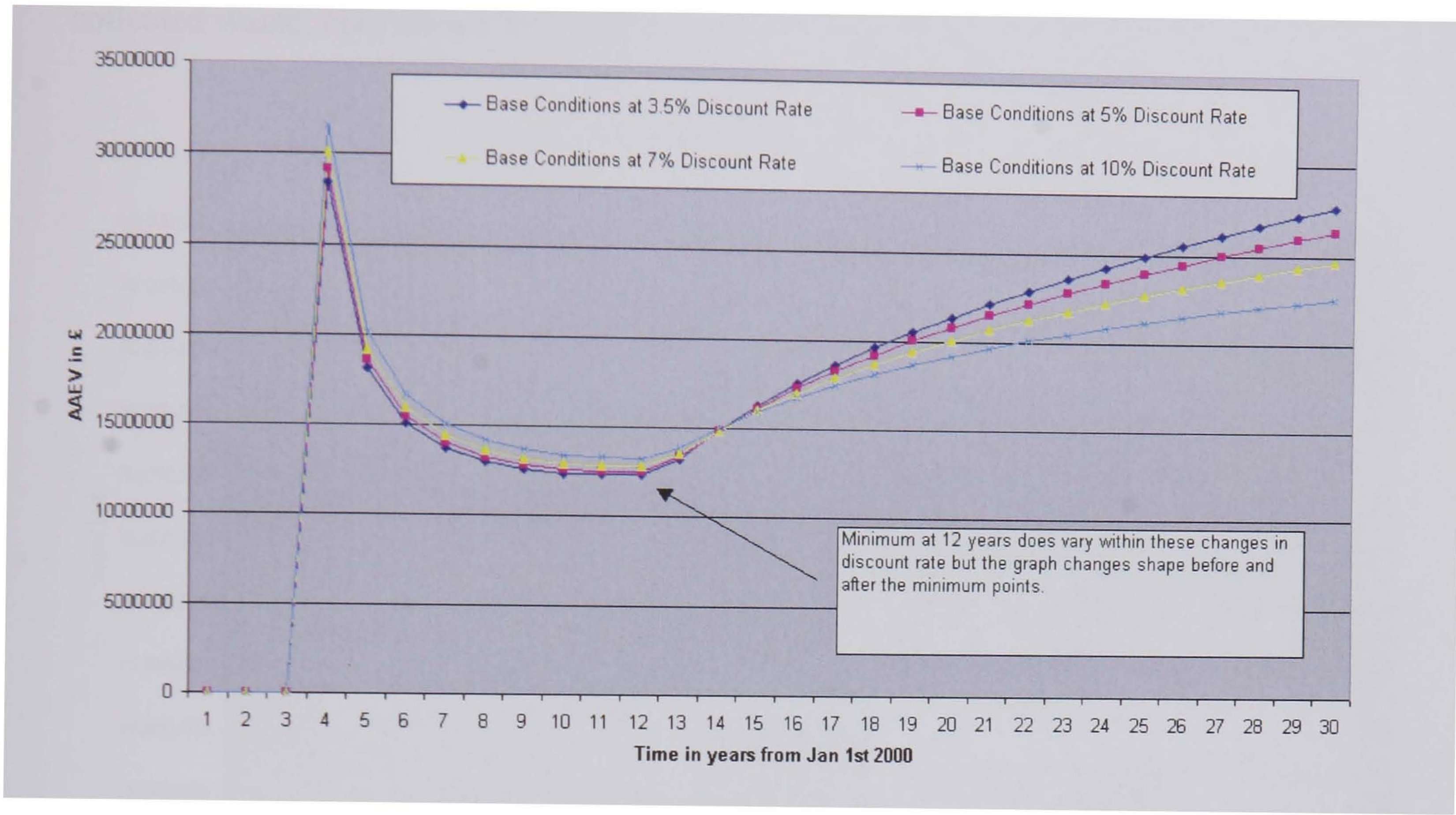
9.2.1 Calculating the Annual Average Equivalent Value (AAEV)

AAEV is calculated by dividing the annual discounted accumulated cost by the discounted discount factor of each year.

$$\mathrm{AAEV}_t = \frac{\text{Discounted total accumulated cost of each year}}{\text{Discounted discount factor of each year}}$$

(See Appendix for a worked example of the calculation process)

9.3 Annual Average Equivalent Value Cost Profiles of the Bedfordshire Sub-region - Medium Term Technology Options



Minimum at 12 years does vary within these changes in discount rate but the graph changes shape before and after the minimum points.

Figure 9.2 – AAEV of the Base Condition at varying discount rate

Figure 9.2 shows:
The Annual Average Equivalent Value (AAEV) of the base condition. Under the current strategy the optimum time to change strategy (technology) is 2012. This is reflected as the minimum point of the curves. This is expected given the sharp rise in operating costs at this point i.e. when landfill capacity in Bedfordshire is exceeded. The variation to discount rate has no effect on the minimum value, but does affect the shape of the curves before and after the minimum points. The scenarios with greater discount rates show a lower gradient i.e. lower increasing rate of costs, after the minimum value. This is as the future value of money is less if the discount rate is greater.

To assess the impact of the timing of technology change and the process of implementation of technology on waste strategy cost and the opportunity for new technology AAEV cost profiles of new technology scenarios are compared to the Base Condition AAEV profile. The medium term strategies designed to achieve the 2015 statutory target for recycling and recovery of 33% of waste, are calculated in AAEV these included:

Scenario 7.5 – Time horizon the recycling through diversification of the plastic waste stream, the composting of collected 'green' waste and the diversion of unsorted waste to a 60ktpa MBT process.

Scenario 7.6 – Time horizon for one phase technology change through the development of a 240ktpa MBT 'Ecodeco' technology with on or off-site incineration of Refused Derived Fuel pellets with 50% diversion.

Scenario 7.7 – Time horizon for one phase technology change through the development of a 200ktpa EfW 'Pyrolysis' technology to process 50% of unsorted collected waste, operational by 2006.

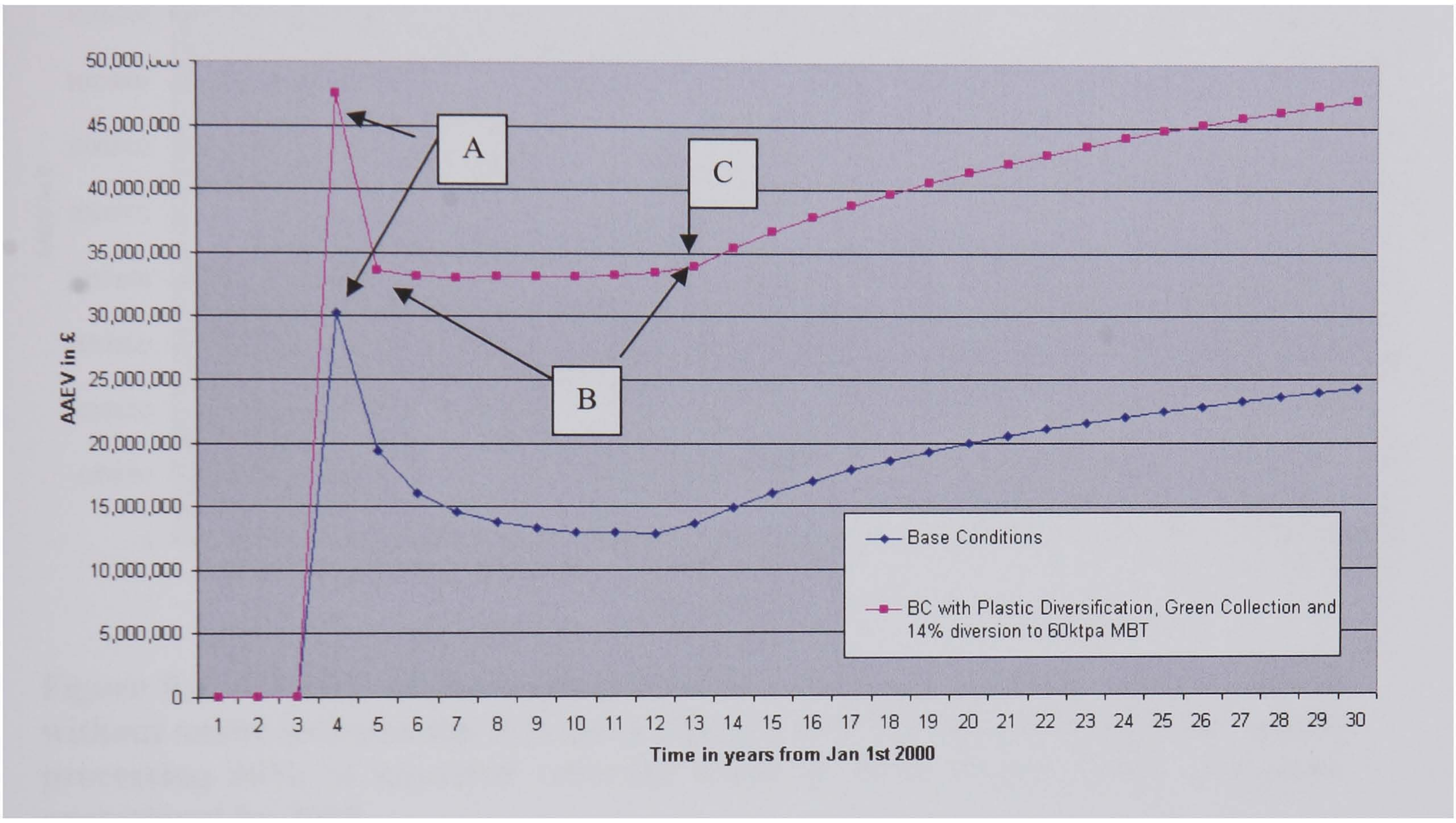


Figure 9.3 – AAEV of technology change through plastic waste diversification at MRF, green waste collection with composting and diversion of 14% of unsorted waste by a 60ktpa MBT 'Ecodeco' process at 7.5% discount rate

Figure 9.3 shows:

- Point A – Initial cost values are £46m compared for the 3 phased technology change scenario.
- Point B – The variation in minimum values within a range of 9 years between 2005 and 2013 identifies that the increase in cost during this period is low. The technology is insensitive to the optimum duration of ownership during this time period.
- Point C – Though not the minimum value costs begin to rise at 2013.

The optimum time to change technology is 2013 i.e. the optimum duration of technology has been extended a year from 2012 in the Base Condition to 2013.

Compared to the annual cost profile of the scenario in Chapter 7 i.e. Figure 7.5, the annual costs are higher. For example between the 2005 and 2014 time period in Figure 7.5 costs are identified at £20m pa and AAEV costs at £33m pa. The increase in costs from the Base Condition is approximately £18m to £20m during this time period in the AAEV cost profiles compared to £12-13m in Figure 7.6. These costs are higher than in Chapter 7, Figure 7.6, as the discount rate is increased i.e. 7.5% compared to 3.5%.

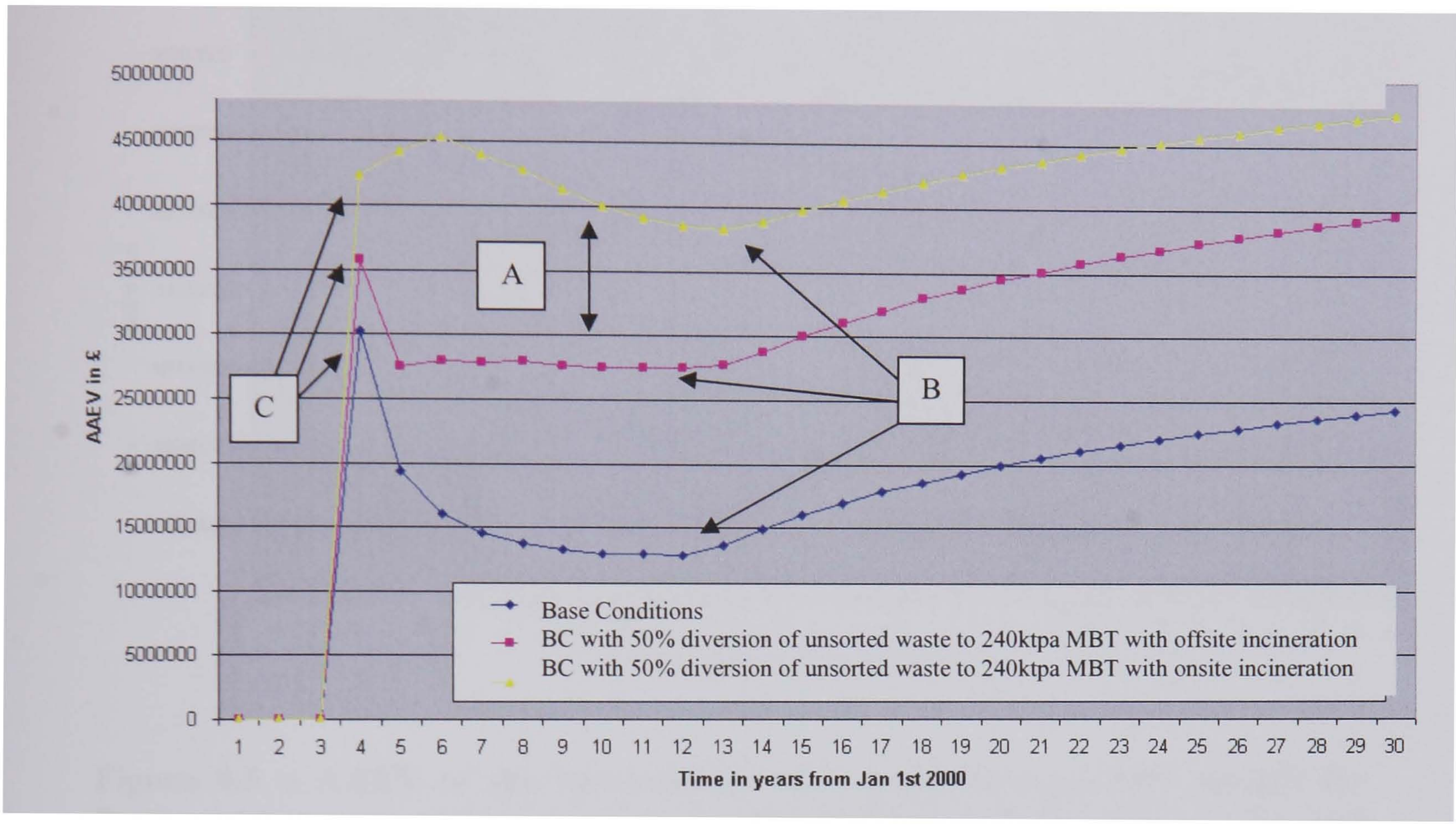


Figure 9.4 – AAEV of the development of a 240ktpa Ecodeco facility with or without onsite incineration through a 200ktpa EfW for the produced RDF pellets processing 50% of unsorted collected waste at 7.5% discount rate and plant operational by 2005

Figure 9.4 shows:

- Point A – The model could be used to identify an optimum gate fee where the cost of developing an on-site 200ktpa EfW facility for the incineration of RDF becomes more favourable than transporting waste to an off-site EfW facility.
- Points B & C – The variation in the minimum values:
  - Base condition – Minimum value £14m at 12 years,
  - Off-site EfW – Minimum value £27.1m at 12 years,
  - On-site EfW – Minimum value £38.2m at 13 years,

The timing of technology change is 2013 compared to 2012 for the Base Condition.

Compared to Figure 7.8 with off-site incineration the annual cost peak is lower at £36m. Between 2005 and 2014 costs are stable around £28m compared to £21m between 2007 and 2013 in Figure 7.8. Therefore the maximum costs are decreasing and the average annual cost increasing between the AAEV and Annual Cost techniques. The general shape of the annual cost profiles is the same.

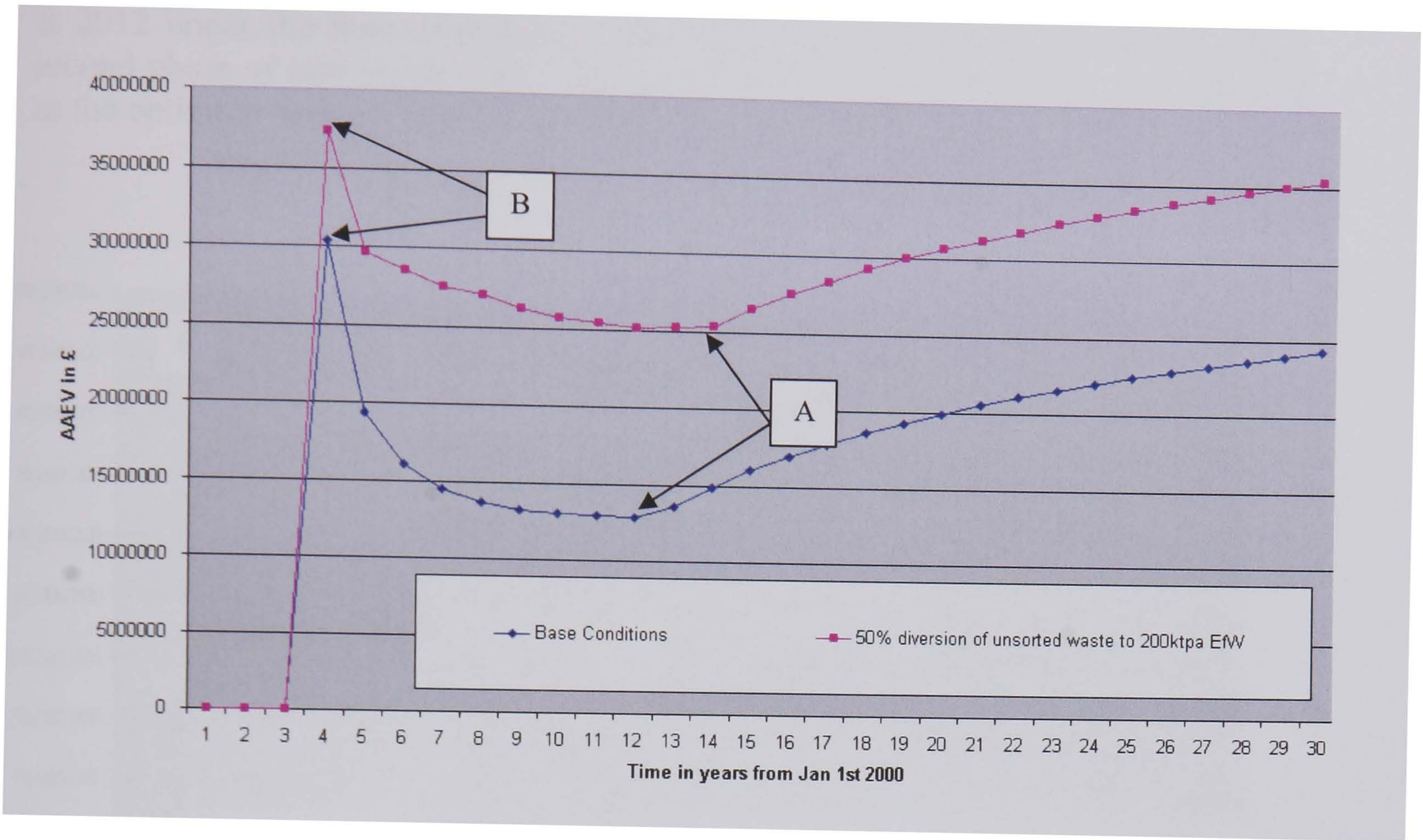


Figure 9.5 – AAEV of the development of a single 200ktpa EfW facility for Bedfordshire to treat 50% of unsorted collected waste at 7.5% discount rate and plant operational by 2005

Figure 9.5 shows:

- Point A – the minimum values of the AAEV curves for the 200ktpa EfW is approximately £25m from 2012 to 2014.
- Point B – the initial values of the AAEV curves for the 200ktpa EfW facility are £37.5m compared to £30m for the base condition

The sharp gradient in the AAEV cost profile for the single phase EfW technology change scenario identifies an increase in costs and sensitive to duration of ownership and the timing of technology change.

Compared to Figure 7.10 the annual cost peak is lower at £37.5m as the capital costs are distributed throughout the lifetime of the technology, this is compared to £53m in Figure 7.10 where capital costs are displayed as a single point investment. As the capital costs are distributed throughout the time period annual costs are generally higher than in Figure 7.10 i.e. between 2007 and 2014 £25m compared to £19m in Figure 7.10. Distributing the costs changes the values of the cost profiles but not the general shape and the timing of cost increases or the need for new technology. The results show the difficulty of identifying costs over time as different calculation methods produce different results and different accounting methods are used to distribute costs over the lifetime of the waste strategy assessment.

9.4 Multiple Phase Technology Innovation – Long-term Results

The previous results have shown the significance of landfill capacity being exceeded at 2012 under the base conditions. Therefore what is the impact of developing a second phase of new technology at this point where the AAEV curves have shown it as the optimum time to change technology.

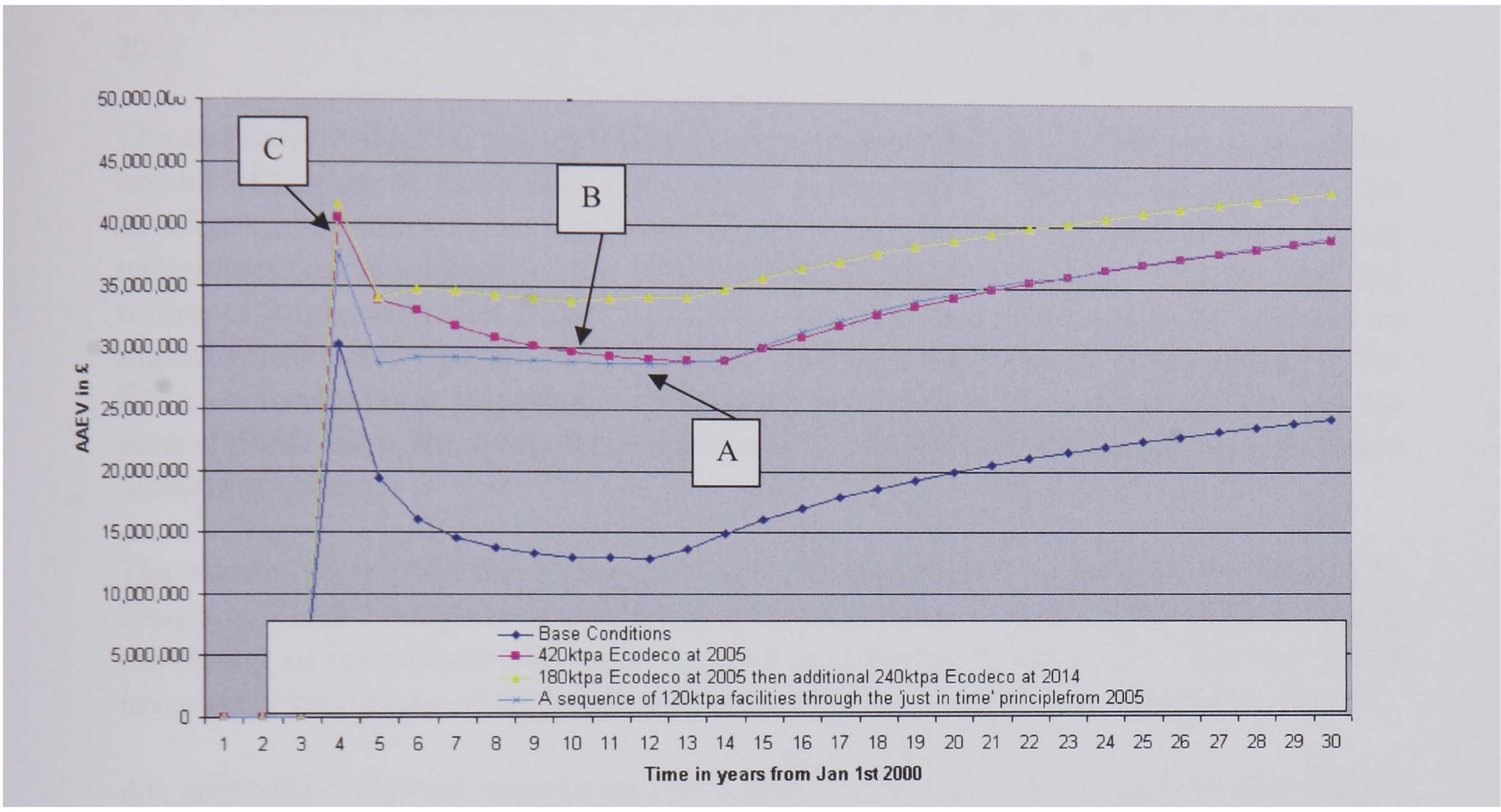


Figure 9.6 – AAEV of Variation through the development of multiple phased MBT 'Ecodeco' facilities to reach 420ktpa operating rate and treat 100% of unsorted collected waste in Bedfordshire at 7.5% discount rate. Phase 1 operational by 2005, phase 2 by 2014.

Figure 9.6 shows:

- Point A – The lowest minimum value is the 'just in time' sequence of developing 120ktpa MBT facilities. This is as the overall cost savings of retaining the capital until the last possible moment reduces the loss of value of money over time.
- Point B – Horizontal gradients for the two and three phased technology change cost profiles show that optimum duration of ownership of these strategies is less sensitive than the single phase technology change that displays greater loss in value of technology. Minimum values
    - BC – 12,874,844 at 12 years
    - One phase, 420ktpa facility - 29,160,100 at 14 years
    - Two phase, 180ktpa and 240ktpa facilities – 33,320,013 at 10 years
    - Three phase, 120ktpa facilities – 28,830,250 at 12 years
- Point C – Initial Capital Values are lowest for the three phase 'just in time' strategy:
    - BC – 12,874,844 at 12 years
    - One phase, 420ktpa facility - £40.5m
    - Two phase, 180ktpa and 240ktpa facilities – £41.6m
    - Three phase, 120ktpa facilities – £37.6m.

9.4 Summary

The results show how different techniques for the calculation of the cost of waste policy and strategy performance vary according to the technique of assessment.

The AAEV curves representing a single phase of technology change show little variation in the utility of strategy with the minimum values (i.e. the optimum lifetime of the technology or strategy) of the AAEV curves being focused around the year 2012.

The scenarios modelled incorporating the two phased technology change, assessed the impact of timing of innovation on strategy performance. The second phase for the development is timed to occur around 2014 i.e. just after the optimum time to change technology, as identified by the single-phase technology results. The process and timing of implementation of new technology through these results is shown to have an impact on the performance of the system. Through delaying the development of the Ecodeco facilities i.e. adopting a 3*60ktpa plant followed by a 4*60ktpa plant at the second phase time, the overall cost of the system is reduced compared to single phase technology change.

The results show that the timing of capital investment is important and though in Chapters 7 and 8 single time events are used to simulate capital expenditure in reality the timing of investment and the process of investment is important. This process of investment being part of the process of innovation as identified in Chapters 1 and 2.

An alternative way of calculating the annual costs would have been to convert the capital costs into £ p t as with the operating costs. But using this technique would have failed to simulate the importance of the timing of costs on strategy performance. Though costs would increase it is not the same as securing the high capital investment that is often necessary for waste management technologies such as EfW and MBT. There is no conclusive answer as to which technique is better as the two techniques display different important issues.

Chapter Ten - Discussion

10.1 Introduction

As identified in Chapter 1, technology innovation is needed to support the development of sustainable waste management systems. The research aimed to investigate the extent to which EU waste policy and its implementation in the UK is stimulating the opportunity for new technology.

In Chapter 1 it was argued that the design of EU waste policy was constraining the opportunity for technology innovation through failure to understand the process of innovation and the dynamic environment within which the system operates.

Three research objectives were identified in Chapter 1 i.e. to investigate the extent to which consideration of:

- EU waste policy and its implementation
- The process of innovation
- The technology assessment technique

Affect the opportunity for technology innovation in an integrated waste management system in the UK.

An evaluation method was needed that allowed investigation of the relationships between policy design, technology assessment and the opportunity for innovation. The method needed to consider the influence of policy and its ability to stimulate technology innovation within a dynamic integrated waste management system.

The thesis has described the development of a modelling tool designed to investigate the cost of new technology options within the wider policy context. The research has produced evidence to investigate the impact of policy, the process of innovation and technology assessment technique on opportunity for technology innovation.

EU waste policy and its implementation in the UK

Individual limitations of policy such as the setting of unfounded targets, the shifting legislative boundaries and the conflict between policy areas were cited in Chapter 1 as examples of how the design of policy was limiting the opportunity for new technology. The research has developed scenarios demonstrating these limitations. For example:

- The model has been used to identify the extent to which the limitations of policy can be justified through identifying the cost of compliance to waste policy through the development of new technology options. For example in Chapter 8, the research identifies the setting of recycling targets as unfounded and creating additional burdens on the opportunity for new technology. The results show that the cost increase to improve the recycling performance is not linear to an increasing recycling rate as resources are not homogeneously located and variables such as distance to market increase.

- The research in Chapters 6 and 8 has identified the importance and value of landfill as a resource. It has identified that though policy is designed to reduce the use of landfill it is actually rewarding owners of landfill resources by making the resource more valuable.
- In Chapter 8, the research has shown evidence to justify the weakness of basing EU waste policy upon single waste materials. Through adopting a single phased technology option the system is less flexible and adaptive to the uncertain environment over time. This means that the system is more sensitivity to uncertainty and technology innovation is less likely to be adopted given the higher risk associated with the system.

Technology Assessment Technique

To investigate the opportunity for new technology an assessment technique was needed that considered technology performance in the wider context of policy. Traditional technology assessment techniques were reviewed and their failure to consider the range of economic, environmental, social and operational factors were cited as a limitation of their ability to assess the opportunity for technology innovation in integrated waste management systems.

- The model has been used to investigate the extent to which barriers to technology innovation created by conflict between the financial and human socio-economic objectives of technology can be overcome. For example in Chapter 7, the modelling results show that scenarios which adopt the Composting technology offer a financially lower cost technology option compared to Plastic diversification technology. But given the human socio-economic opposition to Composting facilities and the NIMBY attitude to new waste facilities this technology option is unlikely to be developed. The results show the additional cost created by the conflict between the economic, environmental and social impact when determining opportunity for new technology.
- Chapter 2 showed that a failure of technology assessment techniques and existing waste management models is their failure to consider the operational demands/constraints of waste process technology options. The research has development a model that allows investigation of the cost of technology and the trade-off with technology efficiency. For example the model allows investigation of the impact of operational issues such as technology shutdowns, varying waste composition and varying waste collection rates on system performance.
- The research has identified the impact of spatial resolution, system boundaries and uncertainty over time on system performance (as identified in Chapter 8). The research has shown how EU waste policy and its implementation constrain the opportunity for new technology. For example the research has shown that through variation to the spatial resolution the cost of developing technology innovation can be reduced as economies of scale and economies of production are realised and the opportunity for technology innovation is enhanced.

The Process of Innovation

The model has been used to investigate the extent to which the process of innovation can affect the impact on opportunity for new technology. The research provides further understanding into technology assessment and what characteristics of technology are needed to achieve long-term strategic objectives. Technology assessment should consider the process of implementation of technology through the timing or aggregation of technology change. Technology assessment should include measurement of the flexibility and adaptability characteristics identified if technology with the ability to sustain performance in an uncertain environment over time is to be achieved.

- The results show that waste management costs are set to rise, as technology is needed to achieve the growing legislative targets. The results identify the high capital costs needed to develop new technology options. The results show how distribution of the timing and process of technology change can offset the need for high capital investment. For example as identified in Chapter 7, through the aggregation and development of a series of smaller scale capacity facilities a system that is flexible and adaptive to uncertainty over time is developed.

In chapter 1 it was outlined in the aim of the research that the hypothesis was that if waste strategy in the UK was not restricted by the need to comply to EU environmental policy could waste strategy performance be improved. The model was designed and developed to help investigate these relationships and the key questions/challenges facing the sector. The results presented in Chapters 7 and 8 of different scenarios modelled give a broad background of information on the capabilities of the model. The results demonstrate the impact of policy on the design of the integrated waste management system and how this affects the opportunity for new technology. The results and analysis demonstrate how the design of the assessment technique can affect the performance of different technology options and impact the opportunity for technology innovation.

To address whether waste strategy could be improved without the constraints of policy specific questions need to be addressed to evaluate the performance of waste strategy. Using the Bedfordshire case study specific challenges facing the waste industry were identified in Chapter 1 to evaluate the extent to which policy is creating an additional burden on waste strategy. These specific questions help determine whether policy is impeding the opportunity for technology innovation and the extent to which policy is stimulating the opportunity for new technology. These questions and challenges result from the design and implementation of waste policy in the UK. The results presented in Chapters 7 and 8 are now used to address these questions:

1. How will the sector (Bedfordshire) deal with the reduced availability of landfill capacity? What impact will this have on the cost of waste strategy?

Policy is challenging the waste sector to reduce its reliance on landfill as a disposal option given the increasing targets for the diversion of biodegradable waste from landfill as described in Chapter 1. The results in Chapters 7 and 8 demonstrate the value of landfill as a resource and show how landfill is financially the most favourable technology option. The results show that when landfill capacity is exceeded in the Bedfordshire sub-region at around 2012 (if current waste strategy is maintained) then the cost of the strategy increases dramatically (as identified in Chapter 6, Figure 6.2) from £40 per tonne to £110 per tonne. The strategy in Bedfordshire is to reduce the importing of waste to landfill to maintain the resources even longer. The modelling results can be used to show how the impact of the policy to reduce the reliance on landfill affects the costs of waste strategy. Through demonstrating the impact of landfill resource on the system performance the policy to reduce landfill resource is going to significantly increase the costs of the waste management system. This is demonstrated in the results in Chapters 6 to 8 as for all technology options to reduce the reliance on landfill the cost profiles show an increase in overall cost. The model results can be used to argue that rather than policy driving technology change and supporting technology innovation it is in fact acting as a barrier to technology innovation. This is as though the policy change is challenging the industry to innovate the cost of innovation, as identified by the results, is predicted to be significantly greater than the existing cost of the integrated waste management system.

Therefore it can be argued that policy does not stimulate the opportunity for technology innovation as given the design of policy the costs of innovation are significantly higher than the costs of the current system? If the cost of different technology innovation options such as MBT or EfW are too be significantly greater than the existing costs of the system (as suggested by the modelling results) what incentive is there for the different stakeholders to support the innovation process? Waste companies responsibly for the management of waste such as the Shanks Group will not be encourage to innovate as the cost of innovation means that either they will have to significantly increase charges for waste management or their profits and shareholder premiums will be reduced. This is already happening to an extent in the UK where Shanks Group has recently sold its landfill operations to the Waste Recycling Group citing the increasing costs of their operations as reasons for their sale (Gascoigne, 2003). The policy to reduce the reliance on landfill has the potential for further complicating the role of local authorities. If waste management companies need to significantly increase their charges for waste management services, how are local authorities going to fund this needed investment? To support the investment in needed new technology in the waste sector either the government needs to significantly increase its contributions of funding to the sector or local authorities need to allocate more of their funds towards waste management. This might be through individual household waste charging schemes or through increases in council taxes.

If policy is to reduce the reliance on landfill by supporting and encouraging the development of alternative technologies policy might be better designed with significant funding subsidies to support such technologies. Possibly through grants, schemes such as the Private Finance Initiative or through tax relief on appropriate technologies. In the UK the increases in landfill tax over the coming years are intended to act as a stick to encourage the reduction in the use of landfill, but they aren't designed to encourage and support the development of new technologies

2. What sensitivity to uncertainty is there to developing strategies (in Bedfordshire) based upon the policy of single material recycling targets?

The results demonstrate the sensitivity of developing waste strategies based upon a single waste material or a single technology such as recycling. In Chapter 8, Figures 8.7 to 8.9 the results show the sensitivity in the Bedfordshire region to the market price for recycled paper, to the distance to market and to waste composition respectively. The results demonstrate that the system in Bedfordshire is highly sensitive to uncertainty of key variables associated with paper recycling, such as market price, distance to market and waste composition. This is reflected in the results by the significant cost changes to the overall systems performance by variation to any of these individual variables. Given that paper market price can have such a significant impact on the cost of the overall system is developing policy in this restrictive approach favourable to strategy performance in the Bedfordshire region?

The results show the sensitivity in the region of designing and implementing policy based upon such single focus policy. The results show that if policy is based upon single material streams and recycling targets in the Bedfordshire region then resources should be allocated to stabilising and maintaining key variables such as markets for recycled, market prices and waste composition. However it can be argued that this sensitivity to the paper market price in the Bedfordshire sub-region is strongly influenced by the fact that in Bedfordshire only 3 waste material streams are currently being recycled i.e. Paper, Metals and Green waste. Therefore it could be argued that if Bedfordshire operated a more diversified waste recycling strategy with say recycling of 10 different material streams, the systems cost and performance would be less sensitive to such variable as paper market price. Would the results show the same sensitivity to paper market price in other regions where more diversification of waste streams and recycling is apparent? This raises issues in the design of the IWMS and of the technology assessment design, by reducing the availability of recycling options and diversity of waste streams into different materials types the system becomes more sensitive to variation of single key variables such as paper recycling market price. In terms of the design and implementation of policy, should policy support greater flexibility and diversity to reduce this sensitivity to uncertainty or should resources be focused on individual key variables such as the paper market? The results highlight the need for policy to have the adaptability and flexibility given the influence of local conditions when planning waste strategies.

3. Does the fragmentation and lack of regional integration created by the implementation of policy affect the cost of waste strategies?

As identified in Chapter 2, Table 2.2, a key conflict of interest in the waste sector is the spatial constraints placed upon waste strategies due to the fragmented structure for waste management in the UK. This is created by the implementation of policy in the UK with often neighbouring local authorities reluctant to collaborate on waste management strategy. This reluctance to collaborate and integrate waste strategies is often based upon unfounded and unsubstantiated ideas such as larger local authorities fearing they would 'carry' smaller neighbouring authorities. The model results can be used to investigate whether this approach to policy implementation and the creation of artificial spatial boundaries to waste management is in fact at additional cost to the management of waste. The results in Chapter 8, Figures 8.1 to 8.6 show the costs of developing an East Anglian waste strategy compared to the Bedfordshire region in isolation. The model results show a decrease in costs of between £4-5 per tonne if waste strategy for Bedfordshire is repeated over the East Anglian region. This shows the potential benefit of adopting a more regionalised and integrated approach to waste management. Policy needs to be better designed to encourage this regionalisation and integration of resources given these potential cost savings that the model results have identified. To encourage innovation through regionalisation of resources in the East Anglian region policy might be better designed forcing authorities to integrate rather than giving them the option of working independently. Here, rather than with the carrot of subsidies, the stick of enforcement might be more appropriate. For waste companies developing new facilities to manage the processing of waste, as the modelling results have shown in Chapters 7 and 8, with larger catchment areas and larger scale facilities cost savings can be realised through economies of scale and production being realised.

4. How do the different levels of policy framework affect the strategy performance and opportunity for technology innovation?

As identified in Chapter 1, a limitation of policy is that it is formulated at the macro spatial level (i.e. EU) it is implemented at the meso spatial level (i.e. nationally) and strategy planning decisions for new technology are based upon the micro spatial level (i.e. local) conditions. The design and implementation of policy often fails to account for local conditions. For example in the Bedfordshire sub-region, local conditions include the proximity to London, the extensive landfill resources due to favourable geological conditions and the revenue generated from importing London waste to the regions landfills. The results demonstrate the reliance on these localised conditions to make strategies less costly and economically attractive. As shown in Chapter 6, Figure 6.5 without consideration of the importation of waste the costs of waste strategy increase significantly by approximately £15-20 per tonne as revenue from the imported waste is lost. The results in Chapters 7 and 8 showing the significant increase in costs when alternative technologies to landfill are modelled concludes that given the types of resources in the Bedfordshire region i.e. landfill, landfill is the most favourable technology option. Given the localised conditions in the Bedfordshire sub-region the policy to reduce the reliance on landfill does in fact have a negative affect on strategy cost and performance. The model results show that designing policy without consideration for such localised conditions rather support sustainable waste management systems it creates an additional burden.

10.2 The Future Design of Policy

The thesis has identified key relationships and trade-offs between technology performance and the opportunity for new technology. The model results have identified relationships (trade-offs) between technology characteristics such as Flexibility and Adaptability that help determined a technology's ability to sustain performance in an uncertain environment.

For example the results show the deficiencies of designing waste technology and environmental policy on single waste stream targets. As described in Chapter 8, in the assessment of the impact of environment uncertainty on paper recycling technology, through developing strategy based upon one phase technology options (such as single waste streams) compared to multiple phase technology options (such as multiple waste streams), technology performance is more sensitive to variation of single variables. Through reducing the aggregation of technology options the flexibility of technology is reduced and the ability to sustain performance in an uncertain environment over time reduced.

Through developing technology with an enhanced ability to sustain performance in an uncertain environment over time, the opportunity for technology innovation is improved as risk associated with the unproven technology is reduced. However this increase in flexibility comes at additional financial cost as identified in Chapter 7.

Given these relationships, policy needs to be designed to focus on technology characteristics rather than individual technologies i.e. recycling or single waste material technology. To stimulate such technology innovation, policy might be redirected through the use of government support and subsidies to promote the development of technology with improved flexibility or adaptability.

If this is to be achieved an understanding or measurement of a technology's flexibility or adaptability is needed. To achieve such an assessment the model would have to be used to investigate whether there was an optimum level of flexibility or adaptability. For example as identified in Chapter 7, flexibility of integrated waste management systems is enhanced through developing an increased number of smaller scale and diverse technology options. This additional flexibility comes at additional financial cost as it is financially more favourable to develop large-scale facilities that enable economies of scale and economies of production to be realised. The model could be used to investigate as to whether there is an optimum level between the number of aggregated sequences of technology, the size of technology and the flexibility of technology to sustain performance in an uncertain environment over time.

The model could be used to investigate whether mathematical relationships could be identified between flexibility and adaptability and a system's ability to sustain performance in an uncertain environment over time. These mathematical relationships could then be used to assess a technology's performance and policy could be designed to stimulate the development of such technology.

The trade-offs identified by the research raise further questions as to the future of waste management in the UK. Given the waste management infrastructure that currently exists a key question is who should bear the risk associated with the uncertainty of technology innovation in waste strategy planning. What might be created in the future is financial trade-offs between the decision actors to bear the risk associated with technology innovation.

As described in Chapter 1, the development of the Private Finance Initiative in the UK waste industry offers an opportunity for the sharing of risks associated with developing new technology between the key stakeholders. The PFI scheme offers a variance on a performance related pay scheme where improved technology performance by the waste companies through achieving and exceeding legislative targets is rewarded through increased payment for services. The aim of the scheme is to encourage technology development beyond the short-term or next legislative target. The model could be used to assess the apportioning and allocation of risks between the stakeholders in such PFI schemes. For example by identifying the cost of adopting different waste technology scenarios with different recycling and recovery rates comparison between scenarios can be assessed to determine the financial cost of improving waste strategy. Through forecasting the benefits of adopting a technology change, if the additional costs do not exceed the financial benefits of the PFI scheme then the technology will not be developed.

10.3 Limitations and Contributions of the research

Limitations identified include:

- The ineffective approach to modelling variation to spatial resolution as identified in Chapter 8. This could be resolved through developing more than one model rather than inputting regional data into the Bedfordshire sub-region model. This would create a more accurate model for investigating the impact of variation to spatial resolution on opportunity for new technology though it would increase the modelling time.

- When interpreting the results of the modelling tool the uncertainty (sensitivity) in results is reflected by the single variation to an individual value. Given the uncertainty associated with so many values this makes interpretation and confidence in results difficult to justify. Confidence in results could be enhanced through modelling scenarios aimed at specific concerns of the operator or stakeholder that is conducting the modelling process. This would create an additional limitation of the work in that the 'value' of the results would be dependant on the knowledge and expertise of the stakeholder conducting the modelling exercise.

- Calibration and validation of the model results could be enhanced through comparing the modelling results with other waste management modelling tools such as the Puragmetum, Mouchel Consulting model.

Contributions identified include:

- The research has provided further understanding into EU waste policy design, technology assessment techniques and the process of innovation. The research has identified relationships between the three when evaluating opportunity for technology innovation in the UK waste sector. The research shows that consideration of the relationships between these components is needed when designing policy if the pathway to stimulate innovation is to be enhanced.

- The European Forum on Integrated Environmental Assessment in the 'Scoping paper for the European Forum on Integrated Environmental Assessment' (2003) highlights the need for an assessment technique that allows investigation of the impact of policy design on integrated waste management systems. The research identifies a methodology for achieving such an objective whilst considering the limitations of existing waste management assessment techniques and models.
- The research provides further understanding of the opportunities for technology innovation in the Bedfordshire sub-region of the UK. The research identifies a technique for investigation into waste strategy planning that can be used to simulate other regions of the UK. The output of the model providing a basis for better communication between the key stakeholders when planning integrated waste management systems and evaluating technology options. The model is currently being adapted to stimulate the Greater London Authority as a part of a further research project. The model is being adapted to evaluate the impact of variation to spatial resolution, through collaboration between local authorities in the Greater London Region, on opportunity for technology innovation.

10.4 Further Work

There are many potential opportunities for further development of the modelling tool in providing further understanding of technology assessment and waste strategy planning in the UK waste industry. The waste management tool has potential commercial application for assisting waste managers in developing waste strategy. The model could be used as a communications tool to assist in identifying the consequences of human socio-economic considerations on technology performance and cost. The work could be used as a basis of developing evidence to challenge the design and implementation of Environmental Policy. The research has identified the relationships and trade-offs between technology performance and technology characteristics such as Resilience, Flexibility and Adaptability. These relationships were a conclusion of the research.. Through further modelling it might be possible to establish a mathematical equation to represent these relationships so that a rule could be established for evaluating technology performance in relation to the process or rate of implementation of technology through aggregation or dis-aggregation of technology.

REFERENCES

Abou Najm, M., El-Fadel, M., Ayoub, G., El-Taha, M., & Al-Awar., F. (2002a) 'An optimisation model for regional integrated solid waste management 1. Model Formulation', *Waste Management & Research*, Vol. 20., No. 1., pp. 37-45, 2002.

Abou Najm, M., El-Fadel, M., Ayoub, G., El-Taha, M., & Al-Awar., F. (2002b) 'An optimisation model for regional integrated solid waste management 1. Model Application and Sensitivity Analysis', *Waste Management & Research*, Vol. 20., No. 1., pp. 46-54, 2002.

Allen P. 'Modelling complex human systems: a fisheries example', *European Journal of operational research.*

Al-Mazidi, S., M., (1992) 'Technology, Planning and Decision Making: Water Resources in Kuwait', MPhil Thesis, Cranfield University.

Al-Mazidi, S., M., (1995) 'Implementation of technology assessment investment techniques on water desalination', *Desalination*, Vol. 103, pp. 39-47, 1995.

Andrews, C. (2001) Unpublished Discussion, Cory Environmental Ltd, Coldbath Square, London, 2001.

Auger, P., Charles, S., Viala, M., Poggiale, J. (2000) 'Aggregation and emergence in ecological modelling: integration of ecological levels', *Journal of Ecological Modelling*, Vol. 127, pp. 11-20, 2000.

Aumonier, S. (2000) 'Making rational decisions in waste management'. IN: Proceedings Waste 2000, Waste Management in the 3rd Millennium, Stratford-upon-Avon, Warwickshire, UK, pp. 152-162, 2000.

Aumonier, S. (2001) 'Identifying the Best Practicable Environmental Option assessment: Application of LCA and other decision-aiding tools'. In Proceedings of the IWM Annual Conference and Exhibition, 'Strength through Diversity', Torbay, June 12-15th, 2001.

Barlishen, K. (1993) 'Decision Support for Municipal Solid Waste Management and Planning', PhD thesis, MacMaster University, Canada. 1993.

Barlishen, K, D., & Baetz, B,W., (1996) 'Development of a decision support system for municipal solid waste management systems planning', *Waste Management & Research,* Vol. 14, pp. 71-86, 1996.

Baetz, B.W. et. al. (1989) 'Trash Management; Sizing and Timing Decisions for Incineration and Landfill Facilities'. *Interfaces*, Vol. 19, No 6, pp. 52-61, 1989.

Barker, S, Kousis, M, Richardson, D and Young, S (Ed) The Politics of Sustainable Development, Routledge, London, p. 91-107.

Bedford News (2004) 'Bedford Borough Council's Best Value Performance Plan Summary', March 5th, 2004.

Bedfordshire County Council (2000a) 'Baseline Report: Developing a sustainable waste strategy for Bedfordshire and Luton', Enviros Aspinwall, Shrewsbury.

Bedfordshire County Council (2000b) 'Analysis of Waste Management Options: Developing a Sustainable Waste Strategy for Bedfordshire and Luton', Enviros Aspinwall, Shrewsbury.

Bedfordshire County Council (2001a) 'Consultation on Waste'.

Bedfordshire County Council (2001b) 'Strategic Sustainability Appraisal'.

Bedfordshire County Council (2001c) 'Bedfordshire and Luton Minerals and Waste Local Plan First Review: First Deposit Draft'.

Bedfordshire on Sunday (2004), 'Rubbish! Some bins will be too laden....', January 18th 2004.

Bedfordshire on Sunday (2004), 'CSD staggard at the loss of £1million tender', February 22nd, 2004.

Bedfordshire on Sunday (2004). 'Residents sweet and sour over compost......', February 22nd, 2004.

Bedfordshire on Sunday (2004) 'Compost plan dumped', March 7th, 2004.

Berger, C., Savard, G., & Wizere, A. (1999) 'Eugene: An optimisation model for integrated regional waste management planning', *Journal of Environment and Pollution*, Vol. 12, No. 2-3, pp. 280-307.

Cargill, A., & Powell, J., (1996) 'Lifecycle assessment and economic evaluation of recycling: a case study', *Journal Resources, Conservation and Recycling*, Vol. 17, 1996, pp. 75-96.

CEC (1994) Commission of the European Communities: Council Directive Concerning Packaging and Packaging Waste, 94/62/EC. Official Journal of the European Communities. 1994.

CEC (1996) Commission of the European Communities: Council Directive Concerning Integrated Pollution Prevention and Control, 96/61/EC. Official Journal of the European Communities. 1996.

CEC (1999) Commission of the European Communities: Council Directive Concerning Landfills, 99/31/EC. Official Journal of the European Communities. 1999.

CEC (2000) Commission of the European Communities: Council Directive Concerning Incineration, 2000/76/EC. Official Journal of the European Communities. 2000.

CEC (2000) Commission of the European Communities: Council Directive Concerning Waste Electrical and Electronic Equipment, [COM(2000)347]. 2000.

CEC (2001) 'A sustainable Europe for a Better World: A European Union Strategy for Sustainable Development', Commission's proposal to the Gothenburg European Council, COM (2001) 264 final. 2001.

CEC (2002) 'Innovation tomorrow: Innovation policy and the regulatory framework: Making innovation an integral part of the broader structural agenda', Louis Lengrand & Associes, Prest (University of Manchester), ANRT, Luxembourg, 2002.

Chang et al. (1997) 'Optimal siting of transfer station locations in a metropolitan solid waste management system', *J. Environ. Sci. Health, Part A: Environ. Sci. Eng. Toxic Hazard. Subst. Control,* Vol. 32A, No. 8, pp. 2379-2401, 1997.

Chartered Institution of Wastes Management (2003) 'Energy from Waste: A good practice guide', IWM Business Services Ltd, Northampton.

Coggins, P, C and Brown, R (1995). 'Waste Statistics: A focus on household waste – How much is it and what is it?'. Paper presented at the 1st National Conference on Household Waste Arisings and Composition, (March 1995, Culham, Oxfordshire).

Coopers and Lybrand, EFTEC and CERGE.(1996). 'Cost benefit analysis of the different municipal solid waste management systems: objectives and instruments for the year 2000'. European Commission, DGXI, Brussels.

Cozens, P. (2001) Unpublished Discussion, Shanks Waste Solutions, Dunedin House, Milton Keynes, 2001.

Crichton, L., Jamieson, D., Ludley, K., and Pannett, L., (2003) 'Separate Waste Collection Systems Best Practice Review', Scottish Executive, 2003.

Defra (2000) Municipal Waste Management Survey 1999/2000, Defra, London.

Defra (2001) Municipal Waste Management Survey 2000/2001, Defra, London.

DETR (2000a). Waste Strategy for England and Wales. HMSO, London.

DETR Strategy Unit (2002). 'Waste not, Want not - A strategy for tackling the waste problem in the England'.

DETR Strategy Unit (2002). 'Delivering the Landfill Directive: The role of new and emerging technologies', Report 0008/2002, Associates in Industrial Ecology, Penrith, Cumbria, UK.

DETR (2001) 'Multi Criteria Analysis'.

Dennison, G., J., & Dodd, V., A., (1998) 'An assessment of the cost of recycling household waste in Britain and Ireland', *Journal Chartered Institute of Water Environment Management*, Vol. 12, No. 3, pp. 202-211, 1998.

Dijkema, G.P.J. & Reuter, M, A., (1999) 'Dealing with complexity in material cycle simulation and design', *Journal of Computers and Chemical Engineering Supplement* S795-S798.

Dijkema, G.P.J., Verhoef, E.V., & Reuter, M, A., (2000) 'A new paradigm for waste management', *Waste Management,* Vol. 20, pp. 633-638, 2000.

Dijkema, G.P.J., Verhoef, E.V., & Reuter, M, A., (2001) 'Managing the Dynamics of Waste Management', Draft for the Third Annual DIOC Symposium, Unpublished. 2001.

DoE (1998). 'Waste management paper no. 26B, landfill design, construction and operational practice – a draft for consultation'. HMSO, London.

DoE (1997) 'A review of the United Kingdom household waste arisings and compositional data', Final report.

DOER (2002). 'Planning Level Cost-Benefit Analysis for Physical Separation at Confined Disposal Facilities'. ERDC TN-DOER-C27, July 2002.

Dosi, G, Freeman, C, Nelson, R Siverberg, G and Soete, L (Ed) (1988) 'Regional waste planning too cumbersome and remote', Technical Change and Economic Theory, Printer Publishers, London.

Downer, J (2003) 'The impact of road transport costs on Waste Recovery and Recycling'. In Proceedings of ISWA World Congress 2003, Melbourne, Australia, Nov 9-14, 2003.

Ecotec Research and Consulting Ltd (2000) 'Beyond the Bin: The economics of waste management options', Ecotec research & consulting.

European Commission (2001) 'Environment 2010: Our Future, Our Choice, 6th EU Environment Action Programme', Luxembourg, 2001.

European Forum on Integrated Environmental Assessment (2003) 'Applying Integrated Environmental Assessment to EU Waste Policy – A Scoping Paper for the European Forum on Integrated Environmental Assessment (EFIEA)', edited by Monkhouse, C., & Farmer, A., Institute for European Environmental Policy, May 2003.

ENDS Report (2001) 'Ballooning waste volumes spell trouble ahead', ENDS Report 317, June 2001, pg. 14.

ENDS Report (2004) 'Second prosecution looms for Britannia over fridge recycling', Jan, 2004.

Environment Agency R&D Technical Report P240 (1997) 'A Review of the United Kingdom Household Waste Arisings and Compositional Data', WRc, Swindon, Wiltshire. 1997.

Environment Agency R&D Technical Report P1-344/TR (2003) 'Waste Pre-treatment: A Review', P A Wheeler & L De Rome, WRc Swindoin, Wiltshire, 2002.

Environment Agency R&D Technical Report P347. (2000) 'A Study of the Composition of Collected Household Waste in the United Kingdom – with Particular Reference to Packaging Waste', WRc, Swindon, Wiltshire. 2000.

Environment Agency (2000) 'Lifecycle Inventory Development for Waste Management Operations: Composting and Anaerobic Digestion'. WRc, Swindon, Wiltshire. 2000.

Environment Agency (2001) 'Strategic Waste Management Assessment: East of England', WRc, Swindon, Wiltshire, 2001.

ETSU (1998) 'An introduction to Household Waste Management', ETSU, Harwell, Oxfordshire, UK.

ETSU (2000) 'Household waste management in the UK – Some examples of current practice', ETSU, Harwell, Oxfordshire, UK.

ETSU (2001) 'Household waste management in the UK – Some examples of current practice', ETSU, Harwell, Oxfordshire, UK.

Ettlie, J (1986) Managing Innovation, Jossey-Bass, San Francisco.

Freeman, H (2002) 'Pay as you throw', *Wastes Management*, May 2002, pp. 18-21.

Forster Wheeler Environmental Corporation and U.S. Army Corps of Engineers (1999) 'Lower snake river juvenile salmon migration feasibility study Anadromous Fish Economic Analysis'.

Gascoinge, C (2002) Unpublished Discussion, Shanks Waste Group, Dunedin House, Milton Keynes.

Gilbert, J and Slater, R. (2000). 'The state of composting in the UK'. *Wastes Management*. Jan 2000, 21-24.

Gladding, T, (2002) 'MRFs – a safe place to work', *Wastes Management* Aug. 2002, pp. 25-27.

Greater London Authority (2003) 'New and Emerging Technologies for Sustainable Waste Management', GLA, City Hall, London, UK.
Greaves C., (1994) 'Waste Policy Formulation and Implementation: Recycling and Landfill', PhD Thesis, Cranfield University.

Gupta, S, K., and Cozzolino, J, M., (1975) 'Fundamentals of Operation Research for Management', California.

Haigh, N (1997) 'Background material for presentation on 'Messages for the future', European Parliament's Committee on Environment: Public Hearing Improving European Waste Management', 26 November 1997, IEEP.

Haigh, N (2003) Manual of Environmental Policy: the EU and Britain, Chapter 5.3, Manly Publishing, Leeds.

Howard (2002) Unpublished Personnel Communicate, Shanks Waste Group, Elstow Materials Recovery Facility, Bedfordshire.

Hogg, D., (2002) 'Costs for Municipal Waste Management in the EU: Final report to Directorate General Environment', European Commission, Eunomia Research & Consulting, Bristol, UK.

Hogg, D., Favoino, E., Nielsen, N., Thompson, J., Wood, K., Penschke, A., Economides, D and Papageorgiou, S. (2002) 'Economic Analysis of options for managing Biodegradable Municipal Waste – Final Report to the European Commission', Eunomia Research & Consulting, Bristol, UK.

Hogg, D, (2003) 'Costs and Benefits of Bioprocesses in Waste Management', In Proceedings of the Euro Summer School Programme, Biotechnology in organic waste management, June 29-July 4th, 2003, Wageningen, The Netherlands.

HM Treasury (2003), 'The Green Book, Appraisal and Evaluation in Central Government', Treasury Guidance, London, UK.

Hubbard, W., (2003) 'Exploring new technologies for municipal waste', *Wastes Management*, June 2003, pp. 40-42.

Hummel, J., (2002) 'Cost effective recycling – Establishing optimum national and local targets', In Proceedings of the IWM Annual Conference and Exhibition, 'Our Sustainable Future', Torbay, June 18th-21st, 2002.

Institute of Wastes Management (2000) 'Materials Recovery Facilities', IWM Business Services Ltd, Northampton, UK.

Javaid, U., M., (2002) 'Analysis of Processes by Integrating Process and Simulation Modelling Paradigms', MSc thesis, Cranfield University, 2002.

Jeffrey, P (1992) 'Managing Diversity: The Strategic Planning of Long Term Technology Infrastructure', PhD thesis, Cranfield University, 1992.

Jeffrey, P., Seaton, R., Parsons, S., Stephenson, T., Jefferson, B., (1999) 'Exploring water recycling options for urban environments: a multi-criteria modelling approach', *Urban Water*, Vol 1, pp 187-200, 1999.

Kao, J, et al. 'Network geographic information system for landfill siting', *Waste Management & Research*, Vol. 15, No. 3, 1997.

Karagozoglu, N., (1993) 'Environmental uncertainty, strategic planning and technological competitive advantage', *Technovation*, Vol. 13, No. 6, pp. 335-347, 1993.

Keeney, R., & Raiffa, H., (1976) 'Decisions with Multiple Objectives: Preferences and Value Tradeoffs', Wiley, New York.

Keeney R., L. (1992) 'Value Focus thinking a pathway to creative decision making', Harvard University Press, London.

King, G (2002) Unpublished Discussion, Milton Keynes Council, Milton Keynes, 2002.

King, G (2003) Unpublished Discussion, Milton Keynes Council, Milton Keynes, 2003.

Kraines, S., Shigeoka, H., & Komiyama, H. (2003) 'A system tradeoff model for processing options for household plastic waste', *Journal of Clean Technology Environmental Policy,* Vol. 4, pp. 204-216, 2003.

Lawver, R, Lund, J, and Tchobanoglous, G. (1990). 'GIGO – a solid waste management model for municipalities'. Proceedings of the Sixth International Conference on Solid Wasre management and Secondary Materials. Philadelphia, USA, Dec 1990.

Light, G.L. (1990) 'Microcomputer Software in Municipal Solid Waste Management: A review of Programs and issues for Developing Countries'. Water Sanitation Paper Series (DP No.6), UNDP-World Bank Water and Sanitation Program, Washington, D.C. 1990.

Lowe, M (2002) Unpublished Discussion. Shanks Waste Group, Dunedin House, Milton Keynes.

Lowe, M (2003) Unpublished Discussion. Shanks Waste Group, Dunedin House, Milton Keynes.

Luning, L, (2003) 'Waste Management at Ecopark De Wierde'. In Proceedings of the Euro Summer School Programme, 'Biotechnology in organic waste management', June 29-July 4th, 2003, Wageningen, The Netherlands.

Lund, L , (1994) 'Linear Programming for Analysis of Material Recovery Facilities', *Journal of Environmental Engineering*, Vol. 120, No. 5, pp. 1082-1094, Sept/Oct. 1994.

Macdonald, M.L. (1996) 'Solid waste management models: A state of the art review'. *J. Solid Waste Technology & Management*, Vol. 23, No. 2, pp.73-83, 1996.

Martin, C., E. & Flanigan, E., (1992) 'Performance evaluation of Materials Recovery Facilities', *Journal of Emerging Energy Technology*, Vol. 41, pp. 111-119, 1992.

Marques, G & Tenorio, J (2000) 'Use of froth flotation to separate PVC/PET mixtures', *Waste Management*, Vol. 20, 2000, pp. 265-269.

McDougall, F., (2001) 'Using Life Cycle Assessment to Aid Waste Management Decisions', In Proceedings of the IWM Annual Conference and Exhibition, 'Strength through Diversity', Torbay, June 12-15th, 2001.

Meeryfield, M (2002) 'Charge-by-weight – Binweight system points the way', *Wastes Management*, May 2002, pp. 24-25.

Mitchell, N. (2003) Unpublished Discussion, Mouchel Parkman, Surrey.

Morley, N 'The current state-of-the-art in sorting and identification of mixed plastic waste', *Polymer Recycling*, Vol. 3, No.3, 1997/8, pp. 217-226.

Morrissey, A., J., & Browne, J. (2004) 'Waste management models and their application to sustainable waste management', *Waste Management*, Vol 24, 2004, pp. 297-308.

National Society for Clean Air and Environmental Protection (NSCA) (2002). 'Relative impacts of transport emissions in recycling', Brighton, June 2002.

OECD (1993) Franscati Manual, OECD, Paris.

Oeltjenbruns, H., Kolarik, W., J., & Schnadt-Kirshner, R. (1995). 'Strategic planning in manufacturing systems – AHP application to an Equipment replacement decision', *Int. J. Production Economics,* Vol. 38, pp. 189-197, 1995.

Ojdemark, C (2002) 'Optical sorting of household waste – a new concept from Scandinavia', In: *Waste Management World,* May-June 2002, ISWA.

Office of Deputy Prime Minister (2002) 'Strategic Planning for Sustainable Waste Management: Guidance on Option Development and Appraisal', OPPM.

Office of Government Commerce (2003) PFI Material.

Parfitt, J, (1997) 'Using GIS in risk analysis: A case study of hazardous waste transport', *Risk Analysis,* Vol. 17, No. 5, pp. 625-633, 1997.

Parfitt, J., Lovett, A., & Sünnenberg, G. (2002) 'Reconstructing the municipal waste stream at a local scale: implications for waste recycling strategies' IN: Proceedings Waste 2000, Waste Management in the 3rd Millennium, Stratford-upon-Avon, Warwickshire, UK, 2000.

Porteous A (1997) 'Life cycle assessment and the waste management hierarchy', Warmer Bulletin. Sept 1997.

Porteous, A (2001) 'Energy from waste incineration – a state of the art emissions review with an emphasis on public acceptability', *Applied Energy*, Vol. 70., 2001, pp. 157-167.

Ramasesh, R., V., Jayakumar, M., D., (1997) 'Inclusion of flexibility benefits in discounted cash flow analyses for investment evaluation: A simulation/optimisation model', *European Journal of Operational Research*, Vol 102, pp. 124-141, 1997.

Recycling & Waste World, (May 2003) 'Bedfordshire smashes targets', pg. 7.

Ross Westerfield Jordan (2003) Fundamentals of Corporate Finance, Sixth Edition, McGraw-Hill, New York, U.S.

Rubenstein, B. 'Multiple Attribute Decision System (MADS): A system approach to solid waste management planning', (1997) Air and Waste Management Association, 90th Annual Meeting and Exhibition 97 – RA134A.02, Toronto, Ontario, Canada.

Rufford, N. (1984). 'The Analysis and Prediction of the Quantity and Composition of Household Refuse'. PhD thesis, University of Aston.

Rulkens, W., M. (2003). 'Overview of Resource Recovery Technologies for Biowastes'. In Proceedings of the Euro Summer School Programme, 'Biotechnology in organic waste management', June 29-July 4th, 2003, Wageningen, The Netherlands.

Salhofer, S. (2000) 'Modelling comercial/industrial waste generation: A Vienna, Austria case study' *Waste Management Research*, Vol. 18, No. 3, pp. 269-282.

Sampson, G. (2001) 'Modelling of Integrated Waste Management Systems', PhD thesis, Cranfield University, United Kingdom. 2001.

Sarkis, J., Presley, A., Liles, D.(1997) 'The strategic evaluation of candidate business process reengineering projects', *Int. J. Production Economics*, Vol. 50, pp. 261-274, 1997.

Scharff, C (2003) 'The waste site story – exploring the NIMBY syndrome', In Waste Management World May-June, 2003, pp. 47-53.

Seaton, R., Black, I., & Longhurst, P. (2003) 'Strategic Waste Catchment Evaluation – CFC'c Removal and materials recovery from Fridges'. Ninth Int. Waste Management and Landfill Symposium – Sardinia 2003, Cagliari, Italy, 6th-10th October.

Sistema Ecodeco (2000) 'Exploiting Municipal Wastes', Ecodeco, Italy, 2000.

Smith, D., J. (2001) Reliability Maintainability and Risk, Sixth Edition, Butterworth-Heinemann, Linacre House, Oxford, UK.

Smith D, G & Baetz, B, W., (1991) 'A Comprehensive Costing Methodology for the Assessment of Solid Waste Management Alternatives', *Journal of Resource Management and Technology*, Vol. 19, No. 4, pp. 140-147.

Stephenson, T., Parsons, S., Seaton, R., (1998) 'The design and development of water recycling technology for sustainable cities'. Cranfield University.

Sundberg, J & Ljunggren, M., C., (1997) 'Linking two modelling approaches for the strategic municipal waste management planning. The MIMES/Waste model and LCA,' Air & Waste Management Association, 90th Annual Meeting & Exhibition, 97-RA134A-06, Toronto, Ontario, Canada.

Sundqvist, J., (2003) 'System analysis of organic waste management schemes-experiences of the ORWARE model'. In Proceedings of the Euro Summer School Programme, 'Biotechnology in organic waste management', June 29-July 4th, 2003, Wageningen, The Netherlands.

Sussams, J., E. (1983) Vehicle Replacement, Gower Publishing, Aldershot, Hants, UK.

Tchobanoglous, G, Theisen, H, and Vigil, S (1993). Integrated solid waste management. McGraw-Hill.

Times & Citizen (March 2nd, 2002) 'Cost savings force introduction of fortnightly waste collection'.

Times & Citizen (February 20th, 2004), 'Mayor sees red over cash snub for orange bag idea'.

Trott (1998) Innovation, FT-Pitman, London.

A. Tukker, J. Hoogendoorn, H. Luiten, K. Schindel, T. Wiedmann,
& U. Albertshauser, (P. Eder, ed.) (2003) 'Scenarios of household waste generation in 2020', Final Report June 2003. JRC/IPTS-ESTO Study.

Tucker, P, Smith D., (1999) 'Simulating household waste management behaviour', *Journal of Artificial Societies and Social Simulation,* Vol. 2, No. 3, 1999.

Wilson, E. University of Louvain-la-Neuve Business School (1998) 'Towards integrated management of municipal solid waste'. University of Louvain-la-Neuve Business School, 1998.

Wheeler, P. et al. (2000) Evaluation of the options for treatment of waste to meet the biodegradable waste targets of the landfill directive. IN: Proceedings Waste 2000, Waste Management in the 3rd Millennium, Stratford-upon-Avon, Warwickshire, UK, 163-170. 2000.

Wheeler, P., (2001) 'Using multi-criteria analysis for waste management decisions', In Proceedings of the IWM Annual Conference and Exhibition, 'Strength through Diversity', Torbay, June 12-15th, 2001.

White, J. A., Agee, M, H., & Case, K, E., (1989) Principles of Engineering Economic Analysis, Wiley, New York.

White, P., R., Franke, M, & Hindle, P. (1995) Integrated Solid Waste Management: A Lifecycle Inventory. Blackie Academic & Professional, Glasgow. 1995.

World Commission on Environment and Development. (1987) Our Common Future. Oxford University Press.

WRAP (2002) 'Plastic Bottle Recycling in the UK', WRAP, Banbury, Oxon.

WRAP (2002) 'UK Paper Mills: Review of current recycled paper usage – Secondary Fibre Study', WRAP, Banbury, Oxon.

Young, D., Scharp, R., & Cabezas, H. (2000) 'The waste reduction WAR algorithm: environmental impacts, energy consumption and engineering economics', *Waste Management,* Vol. 20, pp. 605-615.

Yu, Chang-Ching et al. (2001) 'A comparison of two waste stream qualification and characterisation methodologies'. *Waste Management & Research* Vol.13, No.4, pp. 343-361, 1995.Zenan, P. Unpublished Discussion. Thames Waste Management, Leatherhead, Surrey. 2001

Zanin, P. (2001) Personnel communication. Thames Waste Management

Appendix

Appendix – A Chronology of Environmental Policy affecting the Waste industry in the European Union (adapted from Haigh, 2003)

Year	Environmental Policy	Key Waste Legislation
1972 - 1975	1972. The first International summit on the Human Environment, Stockholm. 1973. The 1st EU Environmental Action Programme adopting the policy 'Prevention is better than cure'.	1975. Council Directive 75/442/EEC on waste. Amended in 1991 and 1996. Key objectives. Members shall prohibit the uncontrolled discarding, discharge and disposal of waste. They shall promote the prevention, recycling and conversion of wastes with a view to their reuse.
1977	The 2nd EU Environmental Action programme, the birth of the 'Polluter Pays' principle.	Implementation of 75/442/EEC directive on waste.
1982	The 3rd EU Action programme, 'the development of environmental considerations into other policy areas'.	
1985	OECD 'Environment and Technical Change' report (1985) identifies that economic prosperity and environmental protection can be compatible. Argues for the development of innovation through regulation.	
1987 - 1989	1987. The Brundtland report 'Our Common Future' (WECD, 1987), identifies the concept of 'Sustainable Development' as a mechanism to achieving economic growth and environmental protection. 1987. The 4th EU Environment Action Programme develops the concept of 'Sustainable Development' into environmental policy. Single European Act 'Environmental protection requirements should be a component of the Communities other policies'.	1989. Council Directive 89/429/EEC on the reduction of pollution from existing municipal waste-incineration plants. . Council Directive 89/369/EEC on the prevention of air pollution from new municipal waste incineration plants. Key objectives of both. The identification of standards for msw incineration plants particularly emissions.
1992	The 5th Environment Action Programme aims to promote Sustainable Development within the Community. United Nations Conference on Environment and Development (UNCED) Rio de Janeiro, Brazil, 1992. It identifies Sustainable Development as policy objective.	

Appendix – A Chronology of Environmental Policy affecting the Waste industry in the European Union (adapted from Haigh, 2003) – Continued

1993	Maastricht Treaty gives environmental action status of an EU policy.	Implementation on amended directive on waste.
1994	Formal establishment of the European Environment Agency	Council Directive 94/62/EC on packaging and packaging waste. Key objectives. To prevent the formation of packaging waste and to recover or reuse packaging waste to reach set target levels.
1996		Implementation on amended directive on waste.
1999	The Amsterdam Treaty makes environmental policy a key political objective of the European Union.	Council Directive 99/31/EC on the landfill of waste. Intended to prevent or reduce the effects of landfill of waste on the environment. Key issues defining of categories of landfill, waste must be treated before landfill and categories of waste can not be landfilled.
2000 - 2001	The 6th Environment Action Programme – still goal for economic development and environmental protection. July 16th 2001 deadline for implementation of the Landfill Directive.	2000. Directive 2000/76/EC on the incineration of waste. Key objective. To prevent or reduce, as far as possible, air water and soil pollution caused by the incineration or co-incineration of waste, as well as the resulting risk to human health. Directive 2000/96/EC on waste electrical and electronic equipment. Key objectives. To promote re-use, recycling and other forms of recovery of electrical and electronic waste in order to improve the environmental performance in the treatment of such waste.
2002	United Nations World Summit Johannesburg identifies the need for partnerships between all stakeholders. Sustainable development not just responsibility of Government regulators.	December 28th 2002 deadline for Implementation of directive on the Incineration of waste.
2006	Target Date for the EU WEEE Directive	Targets include a compulsory household collection target of 4kg,
2008	Target Date for the EU Packaging and Packaging Waste Directive	Targets include recovering 50-60% and recycling between 45% of packaging waste.
2010	Target Date for the EU Landfill Directive (LD) and implementation of Waste Strategy (WS) 2000	LD - To reduce the volume biodegradable waste sent to landfill to 75% of 1995 figures by 2010. WS - To recover value from 45% of municipal waste by 2010
2020	Target Date for the EU Landfill Directive	To reduce the volume biodegradable waste sent to landfill to 35% of 1995 figures by 2010

Appendix - A Review of Technology Appraisal Techniques

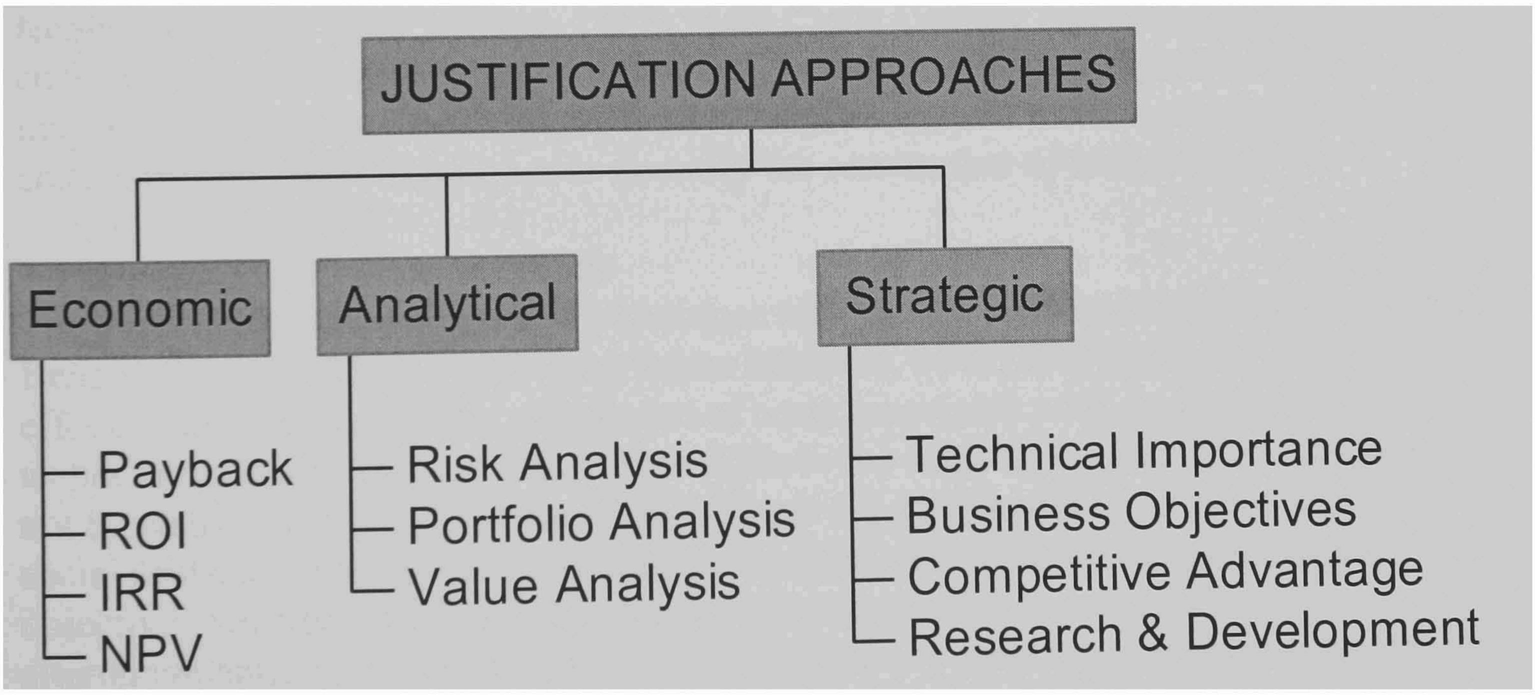
Pre 1990's the vast majority of technology appraisals were based on financial assessments (Jeffrey, 1992). Financial assessments help identify whether technology is affordable, whether capital investment can be attained or whether expected cost savings can be identified (Oxford Dictionary, 2003). Though a financial calculation might provide a favourable assessment of a technology it does not account for the array of technology drivers and influences as described in Chapter 1. The difficulty is identifying a technique that supports assessment for the array of quantitative and qualitative drivers and influences.

This review of technology assessment techniques addresses their ability to understand the interactions and barriers created by the conflict between the financial and strategic objectives of technology. The review assesses the ability of technology assessment techniques to consider these relationships and their influence on the temporality of technology.

Economic, Analytical and Strategic Justification Techniques

Oeltjenbruns et al. (1994) (See Appendix Figure 2.1) reviews the history of technology assessment and identified three categories for technology assessment as Economic, Analytical and Strategic Justification approaches.

Classification of Justification Approaches



Appendix Figure 2.1 - Classification of Justification Approaches (Adapted from Meredith and Suresh 1986 In: Oeltjenbruns et al., 1995.)

Economic Justification Methods
Economic assessment is the identification of opportunity for profit or an expectation to recoup expenditure from a proposal (Oxford Dictionary, 2003). There are numerous Economic justification assessment techniques based upon discounted cash flows (White et al., 1987, Ross et al., 2003). For example:

- Net Present Value (NPV) is the difference between an investment's market value and its cost i.e. how much value is added or lost today by undertaking an investment.
- Payback Period – the time period its takes to recover the initial investment cost.
- ROI – the Return on Investment.
- IRR - Internal Rate of Return is the required return that results in a zero NPV when it is used as the discount rate.

Discounted cash flow (DCF) valuation is the process of valuing an investment by discounting its future cash flows (Ross et al., 2003). The value of £1 today will not be the same in 12 months due to inflation/deflation and the lost opportunity for the money i.e. the potential for generating interest, profit etc. Calculating the discount rate depends on factors such as inflation, 'time preference', the perspective of investor and the time period of assessment. Many researchers in the finance field (Hodder and Riggs, 1984, Myers, 1984, Kaplan, 1986) have argued that DCF techniques should not be abandoned given the importance of 'social time preference'. The value of discount rate used in technology appraisal will be discussed further in Chapter 6, section 6.4.4.

Life Cycle Costing has emerged as an economic justification technique for assessing technology in the 1990's (Rose, 1997). Life Cycle Costing involves identifying the costs over the lifetime of a technology, usually from research design to product disposal. Life Cycle Costing models have been developed which integrate life cycle costs with statistical techniques to quantify the assessment of technology.

Analytical Justification Methods
The most widely used analytical techniques are Cost Effectiveness Analysis and Cost Benefit Analysis (Office of Deputy Prime Minister, 2001, HM Treasury, 2003). Cost effectiveness analysis is the assessment of costs associated with an array of technology options that are designed to achieve the same objective. The costs need not be restricted to purely financial assessment e.g. they could be environmental or social costs, and they are used to identify the least-cost solution of achieving the objective. Cost benefit analysis is the assessment of all the costs and benefits of alternative options in monetary terms. Non-monetary costs such as environmental or social costs are converted into monetary values. If the project benefits exceed loses then it has the opportunity for implementation. Advantages of this method include that it considers the opinions of a range of actors involved in the decision process and values impacts in a single, familiar measurement scale. The converting of non-monetary impacts into monetary values is open to error and does not always take into account the interactions between different impacts.

Other examples of analytical justification methods include Value Analysis, Risk Analysis, Linear Programming and Scoring Models. These methods involve a greater amount of complexity in the assessment process by evaluating more factors including subjective judgements. They require a higher degree of complexity, are more time consuming to generate and more difficult to understand (Oeltjenbruns et al., 1994). Risk analysis techniques became the basis of operational research measuring variability through statistical calculations and probability distributions studies (Webb, 1996).

Strategic Justification Methods

Karagozoglu (1993), states that firms that integrate technology into their strategic planning will achieve a competitive advantage via their product/process innovation. Within a strategic assessment, emphasis is on technology assessment towards factors such as business objectives, competitive advantage and importance for R&D.

Limitations of the Economic, Analytical and Strategic Justification Techniques

Technology that is evaluated economically, analytically or strategically is often not implemented due to other external decision factors (MacDougal, 2001). Economic justification techniques have been criticised for lacking strategic and analytical assessment (Oeltjenbruns et al., 1994). By only evaluating technologies economically long-term benefits such as impact on quality, flexibility and productivity are not included in the justification procedure (Meredith, 1996). They fail to address the relationships between the financial and strategic objectives. They fail to identify the barriers to technology that are created by conflict between these objectives and the resulting impact on technology performance.

Multi-Criteria Analysis

To address the importance of the varying objectives of technology, strategic justification assessment is typically coupled with an economic justification analysis. Multi-Criteria Analysis (MCA) tools have been created to combine technology assessment to include economic, analytical and strategic assessment. MCA evaluates a range of technology options by establishing a set of objectives that can include financial and strategic performance objectives. These objectives are given measurable performance criteria to assess the extent to which they have been achieved by the technology. MCA techniques can be used to identify a single most preferred option, to rank options, to short-list a number of options or simply to distinguish acceptable from unacceptable (Office of Deputy Prime Minister, 2001).

There are different types of MCA techniques such as Linear Addictive models or Analytical Hierarchy Process models. Oeltjenbruns et al., (1994) creates an Analytical Hierarchy Process (AHP). The AHP is an MCA tool that allows simultaneous consideration of financial and non-financial objectives. It uses comparative judgements between pairs of criteria and options to identify a weighting system of influence for each evaluation criteria.

The ability of technology to overcome the barriers created by the interactions between the financial and strategic objectives is based upon these single weightings.
MCA techniques have been widely criticised for the subjective nature of calculating the weightings of performance criteria with their value depending on the perspective of the decision actor. MCA techniques are further limited in that they evaluate technology options of comparable economic life at a single time in an isolated environment. They fail to assess technology of varying economic life and fail to recognise the impact of environment uncertainty on the temporality of technology.

Technology assessment through identification of 'characteristics' of technology and technology systems

Through the identification of technology 'characteristics' a system's ability to sustain performance in an uncertain environment over time can be identified. Through identifying the extent of these 'characteristics' the ability of technology to overcome the barriers between the strategic and financial objectives of technology can be assessed. Jeffrey (1992) identifies these 'characteristics' as relative concepts:

- Resilience – a resilient technology system needs to be a survivor through an ability to achieve long-term performance stability. It is relatively indifferent to uncertainty.
- Robustness – is a measure of how much flexibility is maintained by a technology system, the decision retaining most options for the future is classed as the more robust. A 'process output or product is robust if its performance is insensitive to uncontrollable variations in conditions of manufacture, distribution, use and disposal' (Snee, 1993).
- Flexibility – is 'the capacity to react or respond to changing circumstances.' Flexibility is seen as the options for change or existence of alternative positions/strategies/configurations that the technology system can adopt.
- Adaptability - if flexibility is the potential for change then adaptability is the ability to execute or exploit at that point in time when needed. Hence a technology system maybe flexible but not adaptive. Adaptability is a dynamic process of interaction between a technology system and its environment.
- Diversity – flexibility or adaptability is often accomplished through the utilisation of diversity. Redundancy of technologies raises the issue of over investment.

In recent years the manufacturing sector has developed assessment techniques to measure the flexibility within Advanced Manufacturing Technologies (AMT's). In the manufacturing sector flexibility is viewed slightly differently than by Jeffrey, with flexibility being a measure of adaptability and flexibility i.e. not only a measure of the potential to be flexible but the ability to utilise this flexibility. Swamidass (1988), states that flexibility refers to the ability of the production system to cope with the instability induced by the systems operating environment. Ramasesh et al., (1996) argued that flexibility is highly desirable in manufacturing systems given the ability to switch competitive environment characterised by small volumes, faster delivery times, and shorter product life cycles.

Jeffrey (1992) used technology cost variation i.e. capital, operating and maintenance costs, to measure diversity and resilience in Utility resource systems. The aim was to test strategy resilience against optimisation of system, through variety of technology within the system. Jeffrey showed that the optimal strategy for a production system was an aggregation of various technologies rather than the optimisation of a single technology.

Stephenson et al (2000) identified that 'characteristics' such as the 'modularity' of technology influence the performance of technology. Through assessing a sub-set of wastewater treatment technologies under different assessment techniques they were able to measure the impact of technology on the infrastructure of the wider urban system. They identified the need for 'modularity' of technology to support ease of integration into the wider system. The degree to which systems are designed to accept 'modular technology' can improve the ability of the system to sustain performance in an uncertain environment over time. The extent to which the system accommodates such features as 'modular' technology can assist in overcoming the barriers to technology change.

Jeffrey and Stephenson help identify the need to assess technology of varying economic life. Technology assessment should consider the aggregation/dis-aggregation of technologies to achieve long-term strategic planning rather than appraise alternative single technology options.

Appendix - Sub Models and Variables

a) Waste Collection Processes

1. Household Waste Collection
    - Number of households in the region
    - Growth rate of waste collected
    - Average waste generation per household

    - Percentage served by Bulk collection scheme
    - Percentage served by Orange bag scheme
    - Percentage served by Blue box scheme

    - Paper Fraction
    - Plastic Fraction
    - Metal Fraction
    - Bulk Fraction
    - Green Fraction
    - Glass Fraction

Household Costing Sub Model
- Operating Cost
- Disamenity Cost
- Avoided Burdens Cost
- Environmental Cost
- Transport Cost
- Storage Cost

2. Bring Site Sub Model
    - Inventory of bring waste
    - Growth Rate of bring waste collected

    - Paper Fraction
    - Plastic Fraction
    - Metal Fraction
    - Bulk Fraction
    - Green Fraction
    - Glass Fraction
    - Whites Goods Fraction
    - Textiles Fraction

Bring Site Costings
- Operating Cost
- Disamenity Cost
- Avoided Burdens Cost
- Environmental Cost
- Transport Cost
- Storage Cost

- Revenue from recycling
  - Paper Fraction
  - Plastic Fraction
  - Metal Fraction
  - Green Fraction
  - Glass Fraction
  - Textiles Fraction

3. Household Waste Recycling Centres (HWRC)
   - Inventory of bring waste
   - Growth Rate of bring waste collected

   - Paper Fraction
   - Plastic Fraction
   - Metal Fraction
   - Bulk Fraction
   - Green Fraction
   - Glass Fraction
   - Whites Goods Fraction
   - Textiles Fraction

HWRC Costings

- Operating Cost
- Disamenity Cost
- Avoided Burdens Cost
- Environmental Cost
- Transport Cost
- Storage Cost
- Revenue from recycling
  - Paper Fraction
  - Plastic Fraction
  - Metal Fraction
  - Green Fraction
  - Glass Fraction
  - Textiles Fraction

b) Processing Technology

1. Materials Recovery Facility

MRF Diversification	Sorting Control Switch	Material Capacity
Paper -	On/Off	- Capacity
Plastic -	On/Off	- Capacity
Glass -	On/Off	- Capacity
Metal -	On/Off	- Capacity
Green -	On/Off	- Capacity

- Paper Fraction
  - Newspaper Fraction
  - Office White Fraction
  - Mixed Office Fraction
  - Cardboard Fraction
  - Rejected Fraction

  - MRF Paper Costing
  - Recycling Revenues
    - Newspaper Revenue
    - Office White Revenue
    - Mixed Office Revenue
    - Cardboard Revenue

  - Costs
    - Rejected Cost
    - Paper Sorting Costs
    - Paper Transport Costs
- Glass Fraction
  - Brown Fraction
  - Clear Fraction
  - Mixed Fraction
  - Green Fraction
  - Reject Fraction

  - MRF Glass Costing
  - Recycling Revenues
    - Brown Glass Revenue
    - Clear Revenue
    - Mixed Revenue
    - Green Revenue

  - Costs
    - Rejected Cost
    - Glass Sorting Costs
    - Glass Transport Costs
- Metal Fraction
  - Non-ferrous Fraction
  - Ferrous Fraction
  - Mixed Fraction
  - Rejected Fraction

  - MRF Metal Costing
  - Recycling Revenues
    - Non-ferrous Revenue
    - Ferrous Revenue
    - Mixed Revenue

- Costs
  - Rejected Cost
  - Metal Sorting Cost
  - Metal Transport Cost

Plastic Fraction

- Mixed Fraction
- HDPE Fraction
- Clear PET Fraction
- Coloured PET Fraction
- PVC Fraction
- Rejected Fraction

- MRF Plastic Costing
- Recycling Revenues
  - Mixed
  - HDPE
  - Clear PET
  - Coloured PET
  - PVC

- Costs
  - Rejected Cost
  - Plastic Sorting Cost
  - Plastic Transport Cost

Green Fraction

- Acceptable Fraction
- Rejected Fraction

- Revenue from on-site composting
- Green Transport Cost
- Rejected Cost

2. Composting Facility

Compost Inventory (Not a variable but inflow to sub-model)

- Composted Fraction
- Rejected Fraction
  - Degradation Rate
  - Processing Capacity
  - Storage Capacity
  - Market Capacity

- Costing
  - Operating Cost
  - Disamenity Cost
  - Avoided Burdens Cost
  - Environmental Cost
  - Transport Cost
    - Distance to Market
    - Distance to Landfill
  - Storage Cost

  - Revenue from Compost Sales

3. Energy from Waste Facility

Inventory – Inflow to Facility

- EfW Import Inventory
- EfW Import Growth Rate
- EfW Storage Capacity
- EfW Flow to Landfill
- EfW Storage Capacity
- EfW Residual Fraction
- EfW Processing Rate
  - EfW Costs

    - EfW Residue Disposal Cost
    - EfW Operating Cost
    - EfW Environmental Cost
    - EfW Disamenity Cost
    - EfW Avoided Burdens Cost
    - EfW Storage Cost
    - EfW Bottom Ash Disposal Cost
    - EfW Fly Ash Disposal Cost
    - EfW Overflow to Landfill Transport Costs
    - EfW Overflow to Landfill Environmental Cost
    - Incinerator Tax

    - EfW Revenue from Energy Recovery
    - EfW Revenue from Imported Waste
    - EfW Revenue from Metal Recovery
    - PRN Revenue

4. New Technology Facility (Ecodeco)

New Technology Inventory
New Tech Import Inventory

New Tech Import Growth Rate

- New Tech Processing Rate
- New Tech Processing Capacity
- New Tech Storage Capacity
- New Tech Residual Fraction
- New Tech Recyclable Rate

- RDF export decision destination
- RDT Time
- RDF Distance to destination

  - New Tech Costing

    - New Tech Residue Disposal Cost
    - New Tech Operating Cost
    - New Tech Environmental Cost
    - New Tech Disamenity Cost
    - New Tech Avoided Burdens Cost
    - New Tech Storage Cost

    - New Tech Revenue from Energy Recovery
    - New Tech Revenue from Imported Waste
    - New Tech Revenue from recycling

    - RDF Transport Costs
    - NT Overflow to Landfill Transport Cost
    - NT Overflow to landfill Environmental Cost

5. Landfill Facility

Internal Inventory at Landfill
External Imported waste Inventory
Internal Commercial and Industrial flow to landfill
Variation in import rates
C+I Growth Rate

- Landfill Capacity
- Landfill Processing Rate

  - Landfill Costing
    - Landfill Operating Cost
    - Landfill Environmental Cost
    - Landfill Disamenity Cost
    - Landfill Avoided Burdens Cost
    - Landfill Storage Cost
    - Transport Cost to Landfill
    - Landfill Tax Accumulator

    - Time Factor

Landfill Revenue from Energy Recovery
Landfill Revenue from Imported Waste

c) Strategy Decision Sub-model

Inventory - Inflow of Bulk unsorted waste

Strategy time

- Diversion Fraction to Landfill
- Diversion Fraction to EfW
- Diversion Fraction to New Technology (Ecodeco)
  - Costings
    - Distance to EfW
    - Distance to Landfill
    - Distance to New Technology

    - Transport Cost

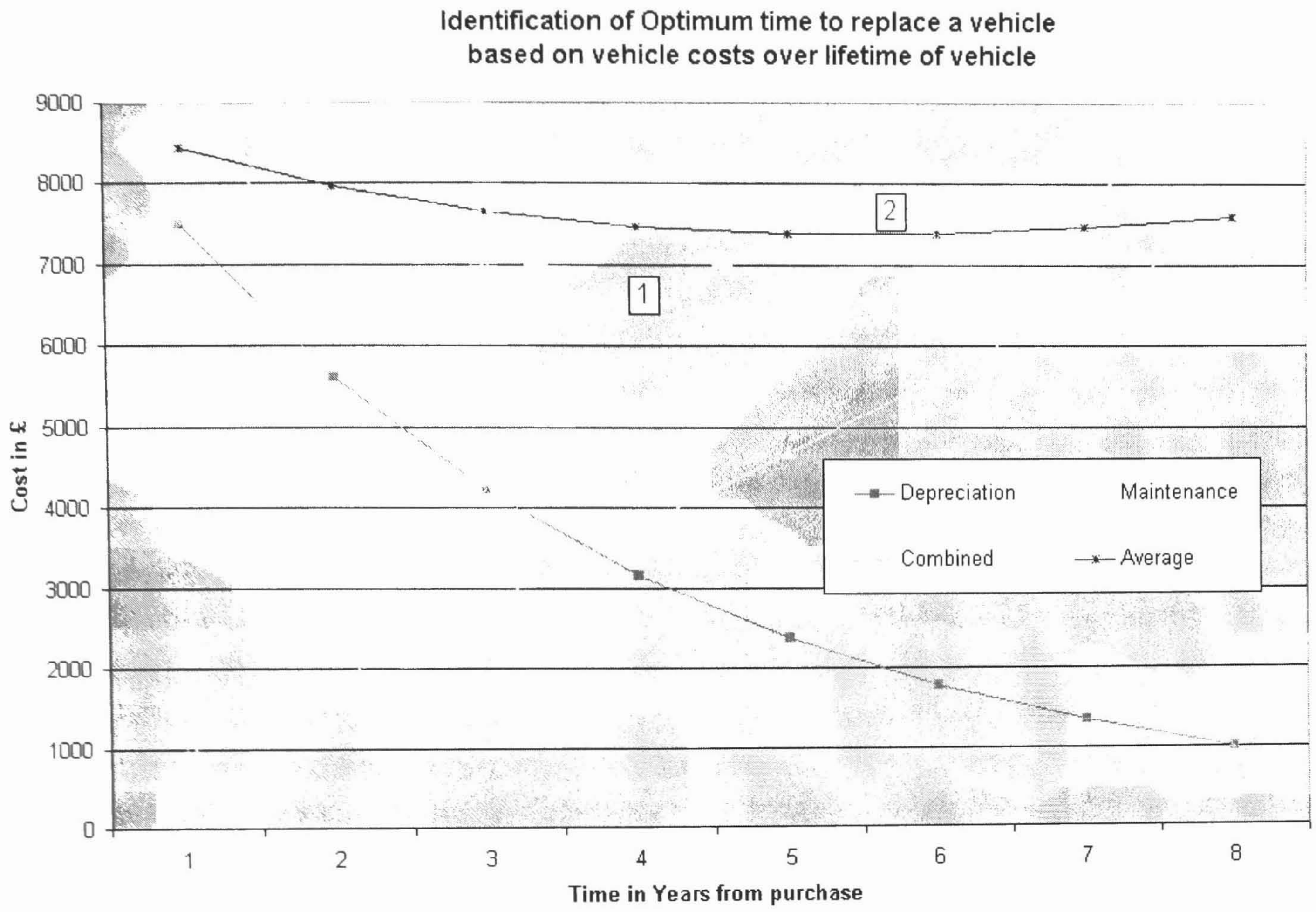
Appendix - Example of AAEV calculation

In making judgements as to when to replace technology in a financial assessment the optimum replacement policy is the one which leads to the minimum total operating cost (Sussams 1973). For example to determine the optimum time to replace a vehicle with purchase price of £30,000 which depreciates at 25% p.a.

The costs of owning a vehicle depends on a variety of factors like fuel, tyres, and servicing, these are classified as Maintenance cost. The loss of value of the vehicle (i.e. the difference between the purchase price and the resale value) is classified as Depreciation cost. The combined cost per annum of the Maintenance and Depreciation costs identifies the annual Operating cost of running the vehicle. The optimum time to replace the vehicle is when the Average Annual Operating cost reaches a minimum value. Before this point Operating costs are still decreasing therefore it is still economically attractive to maintain the vehicle, after this point Operating cost rise therefore it is economically viable to replace the vehicle. A simple model can calculate the optimum time of ownership of the technology.

Year	Residual	Depreciation	Maintenance	Combined	Average
1	22500	7500	937	8437	8437
2	16875	5625	1875	7500	7968
3	12656	4219	2812	7031	7656
4	9492	3164	3750	6914	7470
5	7119	2373	4687	7060	7388
6	5339	1780	5625	7405	7391
7	4005	1335	6562	7897	7463
8	3003	1001	7500	8501	7593

(N.B. Overall the maintenance costs add up to £33,695 which compares to total depreciation calculated at £27,003. This gives a ratio of depreciation to maintenance costs of 1:1.25. In the majority of vehicle assessments depreciation to maintenance costs ratio lies in the range from 1:1 to 1:1.5.)



The graph shows two data points:

1- the minimum value for the combined operating cost

2- the minimum value for the average annual operating cost

It is necessary to find the minimum average operating cost compared to the annual combined operating cost as the costs are then distributed over the lifetime of assessment i.e. the period of analysis.

In this vehicle example as the average for six years is almost exactly the same as the average for 5 years and the average for years 4 and 7 are similar it identifies two policies for vehicle life or replacement. The short-cycle policy to replace the vehicle about halfway through a vehicles life or a long-cycle policy to replace a vehicle when it is no longer worth replacing. In practice this means that the short-policy person will need to find more capital for reinvestment whilst the long-term policy person will need more mechanical investment. Thus the abilities or knowledge of the individual might affect the replacement of vehicles e.g. someone capable of maintaining the vehicle themselves at lower cost than anticipated would benefit from the long-term policy.

The example reviews this basic relationship identifying the optimum timing to change technology. It demonstrates the inadequacies of the technique as it fails to account for the lifecycle costs of the technology and the time value of money. All the costs associated with a technology should be included in the calculation process i.e. the lifecycle costs not just the running costs or depreciation of the technology value. The value of £1 will not be the same in 12months due to inflation/deflation and the lost opportunity for the money i.e. in terms of generating interest, profit etc. The technique only addresses the financial drivers for technology and does not provide a strategic assessment. Later in the thesis this fundamental relationship between the timing of technology and costs will be addressed through the more advanced Annual Average Equivalent Value assessment. This combined with other aspects of the work will provide a more strategic assessment of technology.

The Time Value of Money – Calculating the Average Annual Equivalent Value

The simple example of vehicle replacement identifies the basic principles behind the calculation process, the relationships in identifying the optimum time of ownership of technology. The world is more complicated and further issues need to be considered.

a) The Lifecycle costs – all the costs associated with a technology should be included in the calculation process i.e. the lifecycle costs not just the running costs or depreciation of the technology value. The lifecycle costs should include

- Research and development costs,
- Production and Construction Cost
- Operation and Support Cost
- Retirement and Disposal Cost

b) The time value of money - The value of £1 will not be the same in 12months due to inflation/deflation, the lost opportunity for the money i.e. in terms of generating interest, profit etc. The calculation of the value of money over time is called discounting.

The operating cost is discounted

$$\text{Discounted Operating Cost} = \text{Operating Cost}*1/(1+r)^{\wedge n}$$

Where r is the discount rate and n is the number of years.

The calculation process should include the impact of time on the value of money. The identification of an appropriate discount rate over time is difficult to justify as discount rates vary according to the social time preference rate and inflation. The social time preference rate (STPR) is the rate at which society values money or cash in hand compared to its future value. The UK government identifies a current STPR of 3.5% (Treasury 2003). Therefore if the decision for technology replacement was based on a social or government perspective a discount rate of 3.5% should be applied. For commercial decisions there is greater risk associated with the decision as the company is investing to make a profit or return, therefore higher values of STPR need to be applied.

Calculating the Annual Average Equivalent Value (AAEV) (note uses mid points of years not end of years)

The aim of the calculating process is to step through the successive years of ownership until a minimum AAEV is obtained. This time period is the minimum discounted cost of owning and operating the asset. The steps of the calculation process assuming a discount rate of 5%:

(i) The annual operating cost is discounted

Discounted Operating Cost = Operating Cost* 1/(1 + r)^^{n}

Where r is the discount rate and n is the number of years

Year	Discount Factor (5%)	Operating Cost	Discounted Operating Cost	Cumulative Disc Operating Cost
1	1	937	937	937
2	0.9524	1875	1785	2722
3	0.9070	2812	2550	5273
4	0.8638	3750	3239	8512
5	0.8227	4687	3856	12368
6	0.7835	5625	4407	16776
7	0.7462	6562	4896	21672
8	0.7107	7500	5330	27002

(ii) The residual value (or salvage value) of the technology is calculated, this will normally decrease with time or can be zero.

(iii) The capital costs are discounted to provide the discounted value of the capital costs at some time in the future. The capital cost is discounted at the **mid-point** of each year. (Within the applications of AAEV identified in the review the capital costs can be discounted to the mid-point or end of the year, this can slightly affect the values calculated but does not impact the general shape and timings of the minimum points of the curves).

Year	Capital Cost (Residual value)	Discounted Capital Cost
0	30000	30740
1	22500	21957
2	16875	15684
3	12656	11202
4	9492	8001
5	7119	5715
6	5339	4082
7	4005	2916
8	3003	2082

(iv) The loss of asset value is identified as the difference between the initial investment cost and the discounted residual value of the technology.

Discounted loss of value = Capital Cost – Capital Cost discounted at next year

Year	Capital Cost Discounted	Discounted loss of value
0	30740	
1	21429	8783
2	15305	15056
3	10932	19538
4	7809	22738
5	5577	25025
6	3983	26658
7	2846	27824
8	2032	28658

(v) The total discounted accumulated cost is the sum of the discounted operating cost and the discounted loss of value

Discounted total accumulated cost = Discounted Operating Cost +
Discounted loss of value.

Year	Cumulative Discounted Operating Cost	Discounted loss of value	Discounted total accumulated cost
1	937	8783	9720
2	2722	15056	17779
3	5273	19538	24811
4	8512	22738	31251
5	12368	25025	37393
6	16776	26658	43434
7	21672	27824	49496
8	27002	28658	55660

(vi) The discount factor is discounted to reflect uncertainty over the time horizon, it is equal to one at the first year and for other years it is calculated as follows:

Discounted Discount Factor = Previous year discounted discount factor + $1/(1+r)^{\wedge n-1}$

Year	Discounted Discount Factor
1	1
2	1.95
3	2.86
4	3.72
5	4.55
6	5.33
7	6.08
8	6.79

AAEV is calculated by dividing the annual discounted accumulated cost by the discounted discount factor of each year.

$$AAEV_t = \frac{\text{Discounted total accumulated cost of each year}}{\text{Discounted discount factor of each year}}$$

Year	Discounted total accumulated cost of each year	Discounted discount factor of each year	AAEV
1	9720	1	9720
2	17779	1.95	9106
3	24811	2.86	8677
4	31251	3.72	8393
5	37393	4.55	8225
6	43434	5.33	8149
7	49496	6.08	8146
8	55660	6.79	8201

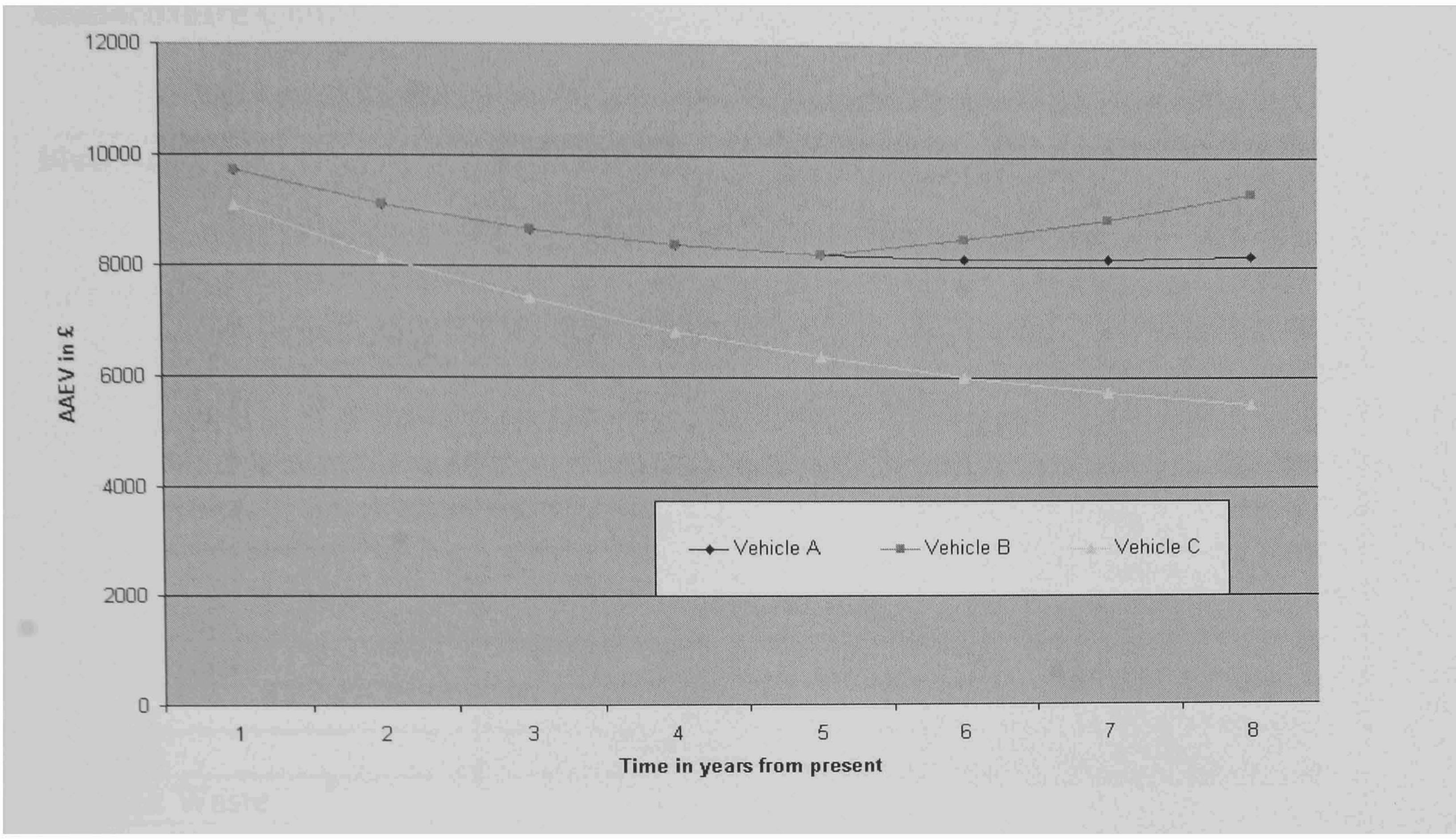
Variations to the theme and comparison between vehicles

Year	Vehicle A	Vehicle B	Vehicle C
1	937	937	300
2	1875	1875	600
3	2812	2812	900
4	3750	3750	1200
5	4687	4687	1500
6	5625	8000	1800
7	6562	10000	2100
8	7500	12000	2400

Vehicle A is the operating costs associated with vehicle type A.

Vehicle B shows a dramatic rise in operating cost at year 6 as the vehicle is shown to have a fundamental flaw with its engine.

Vehicle C displays a much better performance in operating cost as it is more efficient.


AAEV Curve for a £30,000 vehicle with a lifetime of 8 years

Analysis

The graph shows that the minimum point of the curves and the optimum time to change vehicles varies as operating cost vary. For vehicle type A the minimum occurs at between 6-7 years. In vehicle type B where the vehicle type is beset with engine problems after 6 years the optimum time to change vehicles is before these costs occur at 5 years. In vehicle type C which operates with improved performance the operating costs are much lower meaning the vehicle does not need replacing within the time horizon of assessment.

Appendix - Household Waste Composition Bedfordshire 2000 (Adapted from Bedfordshire County Council, 2003)

Material Type	Bedfordshire (National Household Waste Composition)	Luton (MEL Composition Analysis, October 1999)
Newspapers	19.0 %	18.9 %
Other Paper	8.1 %	6.8 %
Cardboard	4.9 %	5.9 %
Plastic Film	5.0 %	3.3 %
Plastic	5.8 %	4.8 %
Glass	8.9 %	7.4 %
Steel	5.2 %	2.4 %
Aluminium	2.0 %	0.7 %
Mixed Metals	1.0 %	0.2 %
Fines	7.0 %	3.2 %
Textiles	2.0 %	2.7 %
Kitchen Waste	17.5 %	12.8 %
Garden Waste	3.5 %	11.0 %
Other	10.1 %	19.9 %

Appendix – Changing the model variables to simulate different waste strategies as represented by different model

Figure 6.4 – Set variable MRF processing rate and capacity to change from 0 to 60ktpa at 2006.

Figure 6.5 – Set landfill capacity variable to 0, change the imported waste variable to 0

Figure 7.1 – Set the plastic diversification decision variable from 0 to 1 with timing delays of when it becomes applicable i.e. at 2006, 2008 and 2010

Figure 7.2 – Set the green waste collection variable to increasing green waste collection at 2003, change the composting processing rate variable by increasing capacity by 20ktpa at 2019

Figure 7.3 – Set the green waste collection variable to increase as in Fig. 7.2 with the changes to the plastic diversification decision variable as in Fig. 7.1

Figure 7.4 – Set as in Fig. 7.3 with the additional changes made in Fig. 7.2. to the composting capacity

Figure 7.5 – Set as in Fig 7.4 with additional changes to the landfill diversion rate variable from 100% to 86% and the diversion to MBT variable from 0% to 14%, with changes to be operational at 2006. Set MBT variables processing rate, storage capacity and costs to reflect a 60ktpa MBT facility

Figure 7.6 – As in Fig. 7.5 with capital costs added to the cost profile

Figure 7.7 – Set the variable diversion of unsorted waste to landfill from 100% to 50% and the variable diversion to MBT facility from 0% to 50% with changes operational at 2006. Set the processing rate, storage capacity and costs of the MBT facility to reflect a 240ktpa facility

Figure 7.8 – As in Fig. 7.7 with capital costs added to the cost profile

Figure 7.9 – Set the variable diversion rates to landfill from 100% to 10%, 30% and 50% and the variable diversion rate to EfW from 0 to 90%, 70% and 50% respectively. Set up EfW processing rates, storage capacities and costs to reflect a 200ktpa EfW facility. Set changes to occur at 2006

Figure 7.10 – As in Fig. 7.9 with capital costs added to cost profile

Figure 7.11 – Set the variable diversion rate to landfill from 100% to 0% and the variable diversion rate to MBT from 0% to 100% to occur at 2006, 2014 and 2020. Set MBT variables processing rate, storage capacity and costs to reflect changes in MBT capacity as identified i.e. to 420ktpa at 2006, a sequence of 120ktpa facilities at 2006, 2014 & 2020 and a 180ktpa facility at 2006 & a 240ktpa facility at 2014.

Figure 7.12 – Change as in 7.11 with capital costs added to an annual cost profile

Figure 8.1 – Support model with East Anglian regional data

Figure 8.2 – As Fig. 8.1

Figure 8.3 – Change variable diversion rate to landfill from 100% to 25%, 50% and 75%, change variable diversion rate to EfW from 0% to 75%, 50% and 25% respectively. Set EfW facility variables to a1600ktpa facility, change transport distance to EfW variable as identified in Chapter 4

Figure 8.4 – As Fig 8.3 with capital costs added to annual cost profile

Figure 8.5 – Change variable landfill capacity and processing rate 1000 fold, change diversion rates to landfill from 0% to 100%, change diversion rate to EfW from 0% to 100%, time changes to occur at 2005. Set up EfW variables processing rate, storage capacity and costs to a 400ktpa EfW facility. Change variable transport distance to EfW as identified in Chapter 4.

Figure 8.6 – As in Fig. 8.6 with capital costs added to annual cost profile

Figure 8.7 – Change paper market price variable to reflect different strategies i.e. reduce by 50%, increase by 100% and random between 0-100 pounds

Figure 8.8 – Change the paper distance to market variable to reflect changes to distance to market, i.e. to 10km, stepped to 825 & 968km at 2010 & 2021 respectively, and gradually up to 1000km

Figure 8.9 – Change waste generation variables to reflect gradually changing waste composition as identified in Table 4.2

Figure 9.3 - AAEV of Figure 7.5

Figure 9.4 – AAEV of Figure 7.7

Figure 9.5 – AAEV of Figure 7.9

Figure 9.6 – AAEV of Figure 7.11