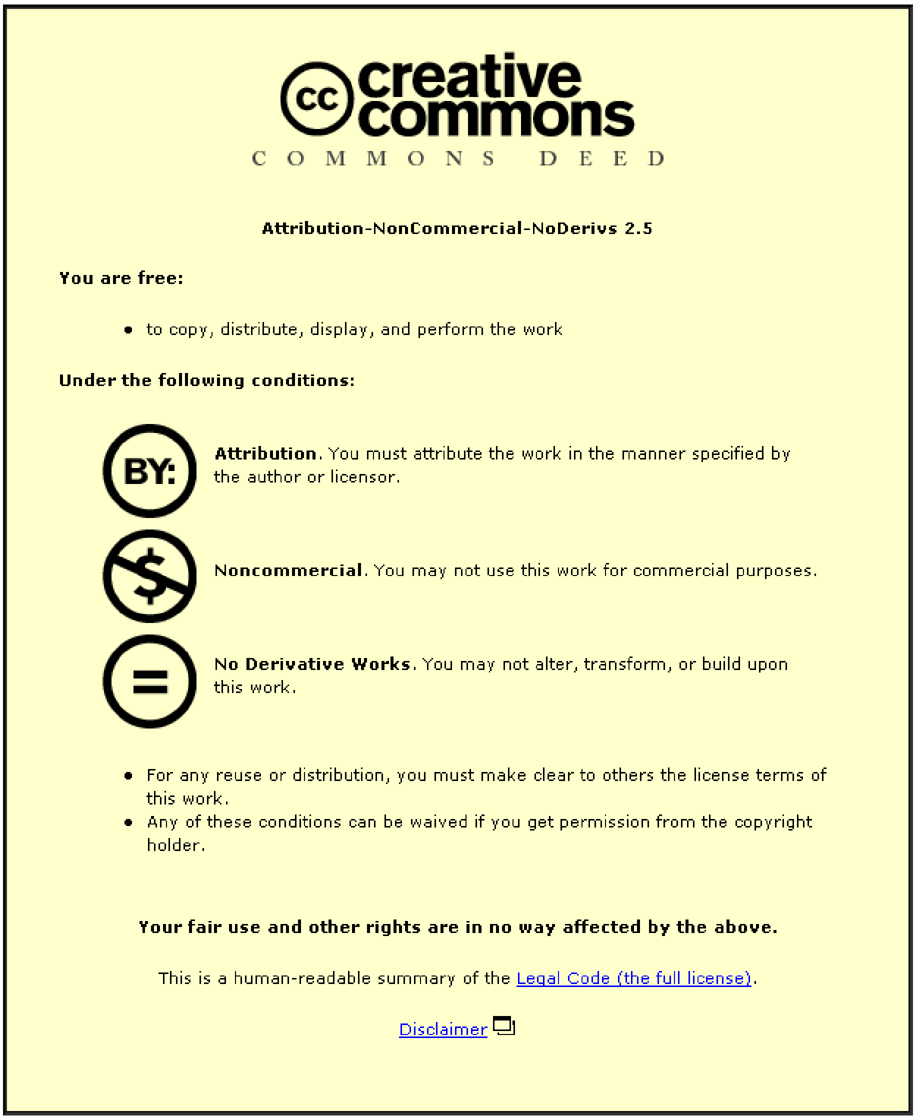

A Framework for supporting the sustainable adoption of biopolymers in packaging applications

by

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A Doctoral Thesis

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Synopsis

This thesis reports on the research undertaken to investigate the reduction of the environmental impacts of plastic packaging through the effective selection and application of biopolymers during the pack design process. The principle objective of this research is to develop an understanding of the strengths and weaknesses of biopolymers as a packaging material and to develop a framework which enables biopolymers to be considered at each stage of the pack design process to enable their effective and appropriate selection and use.

The research contributions can be considered in four main parts. The first comprises of a comprehensive review of plastics packaging including the key polymers used (conventional and bio), their social and environmental impacts, main production methods and packaging applications (for biopolymers this included a market review of recent biopolymer pack introductions). When considered against the available life cycle assessment literature and current range of available eco-design tools and methods, the review concludes that the current understanding of the sustainability benefits from using biopolymers in packaging is still not fully understood and the range of tools to support their application during the packaging design process are inadequate.

The second part of this research defines a framework to support the improved sustainability of plastics packaging through the effective selection and application of biopolymers during the eco-design process. This is achieved through the identification of a systematic approach, which supports the decision process each key stage of the pack design process. The framework identifies the need to: evaluate the potential for biopolymer to contribute towards the company’s sustainability strategy; to provide a mechanism to communicate those strategic objectives into actionable design criteria; to identify the most appropriate biopolymers to meet the companies technical, commercial and strategic requirements; and to ensure that at each subsequent stage of the design process, the original strategic intent is considered as part of the evaluation and selection criteria.

The third part of the research is concerned with the development of a computer aided, decision support tool for the design of biopolymer packaging, which combines a multi-layered biopolymer database to support material selection and design evaluation at various levels of complexity, as required by each of the key framework stages, and to provide a multi-criteria evaluation method that combines a novel impact assessment tool for evaluating the strategic requirements, alongside existing life cycle assessment and cost benefit analysis methods and tools to assess the overall performance of the pack design. The decision support tool builds on existing knowledge and methods of sustainability assessment to provide a comparative performance indicator of a particular design current and future sustainability impacts.

The final part of this research demonstrates the validity of the framework and tool through the completion of two case studies based on a combination of real and simulated data. These case studies demonstrate the influence of ‘soft’ factors (company strategy, culture etc.) on the design direction as opposed to the more obvious ‘hard’ factors such as product and production requirements. This highlights the importance of providing design support at the strategic level which is lacking in other packaging eco-design methods and tools.

In summary, the research concludes that the use of biopolymers by a company for its packaging does not automatically guarantee an environmental improvement; in fact the inappropriate use or incorrect selection of biopolymer may significantly increase the company’s environmental footprint, causing long term environmental, social and economic harm to the business, supply chain and markets. It has been shown that consideration of biopolymers against the strategic objectives during the initial stages of the design process can ensure the subsequent efficient use of company’s design and development resources and the avoidance of costly packaging development that do not meet the company’s original sustainability objectives.

Abbreviations

AHP	Analytic Hierarchy Process
Bio-PE	Bio-derived Polyethylene
Bio-PET	Bio-derived Polyethylene Terephthalate
Bio-PP	Bio-derived Polypropylene
BSC	Business Score-Card
CASPPa	Computer Aided Sustainable Plastic Packaging
CCME	Canadian Council of Ministers for the Environment
CH_4	Methane
CO_2	Carbon Dioxide
COMPASS	Comparative Packaging Assessment
CSR	Corporate Social Responsibility
DfE	Design for Environment
DM	Data Module
EC	European Commission
EoL	End-of-Life
EP	Eutrophication Potential
EPS	Expanded Polystyrene
EU	European Union
EVOH	Ethylene Vinyl Alcohol
GHG	Green House Gases
GWP	Global Warming Potential
HDPE	High Density Polyethylene
HFCS	High Fructose Corn Syrup
ISIS	Integrated Sustainable Inclusive and Strategic
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LDPE	Low Density Polyethylene
LLDPE	Linear Low Density Polyethylene
MEG	Mono-Ethylene Glycol
NGO	Non-Government Organisation
NIR	Near-Infrared
PDS	Packaging Design Specification

PE	Polyethylene
PET	Polyethylene Terephthalate
PHA	Polyhydroxyalkanoates
PHB	Polyhydroxybutyrate
PLA	Polylactic Acid
PM	Processing Module
PP	Polypropylene
PS	Polystyrene
PTA	Purified Terephthalic Acid
PVA	Polyvinyl Alcohol
PVC	Polyvinyl Chloride
RC	Regenerated Cellulose
R&D	Research and Development
SBSC	Sustainable Balanced Score-Card
S-LCA	Social Life Cycle Assessment
SPA	Sustainable Packaging Alliance
SPaBSC	Sustainable Packaging Business Score-Card
SPDF	Sustainable Packaging Design Framework
sPDS	‘strategic’ Packaging Design Specification
SPPaC	Sustainable Plastics Packaging Checklist
TFM	Top Financial Measure
tPDS	‘technical’ Packaging Design Specification
TPS	Thermoplastic Starch
UIM	User Interface Module
UV	Ultraviolet
VOC	Volatile Organic Compound
WRAP	Waste Action Resource Program

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Chapter 1 Introduction

During the relatively short period that humans have occupied the Earth, the planet has shown an almost limitless capacity to provide the natural resources needed to support human life, whilst absorbing the resulting waste produced. However, since the rise of industrialisation in the 18th Century, the damaging impacts of human activities on the planet's ecosystems and resources have become increasingly apparent; e.g. global warming, eutrophication, pollution, deforestation, extinctions and ozone depletion. There is now a general consensus among researchers that the modern lifestyles, enjoyed by the highest consuming 15% of the planet's population living in the developed world, are not sustainable. In response, concerned governments have introduced environmental legislation to regulate some of societies more harmful activities. Packaging was one of the first consumer product sectors in Europe to be targeted with specific legislation designed to control its production, use and disposal. The European Union (EU) Directive of 85/339/EEC on beverage packaging was introduced in the mid 1980's, followed by the broader EU Directive 94/62/EC on the management of all packaging waste in 1994 (European Commission, 2010). As a result of the various legislation introduced by EU members, the packaging industry has been at the forefront of many initiatives to improve the sustainability of its activities and products including material substitution, reduction, recovery, re-use and recycling.

Conventional plastics packaging has, to a degree, been a victim of its own success. A combination of affordability, versatility and durability has seen the use of plastics in packaging increase dramatically since their discovery and commercialisation in the mid-20th century. The use of plastics generally has also significantly increased over the past 70 years, becoming ubiquitous in almost all aspects of our modern lives; packaging however remains the largest end use sector. This commercial success of conventional plastics as a packaging material and its ability to resist degradation by natural processes has resulted in the growth of a highly visible post-consumer waste stream. The majority of this 'post-consumer' waste is still sent to landfill or if unmanaged, can contaminate the environment as litter. Furthermore, the majority of conventional polymers in use today are manufactured from fossil based resources such as crude oil, natural gas and coal (American Chemistry Council, 2005). These non-renewable, finite resources are being rapidly depleted by a wide range of human demands, the most significant of which are as fuels for energy production, heating and transport; fossil fuels currently provide approximately 80% of the world's primary energy needs (Goldemberg, 2006). Whilst plastics production accounts for only 4-5% of global crude oil consumption, a large proportion of this is used for packaging (Quieroz & Collares-Quieroz, 2009) (Plastics Europe, 2009).

Resource depletion is only part of the problem; carbon dioxide produced when these fossil fuels are burnt is a major contributor to global warming (Gärtner & Reinhardt, 2004). As demand for fossil fuels continues to increase, so the pressure to find new reserves pushes exploration into increasingly challenging and environmentally sensitive locations, compacting the environmental impact of extraction and use (Bergerson & Keith, 2006), (Howarth, *et al*., 2011). Biopolymers, polymers derived from renewable (biological) resources, offer a partial solution to these problems by meeting the growing demand for plastics without depleting valuable fossil fuel reserves. Furthermore the production and use of biopolymers, compared to conventional polymers, are often claimed to be less environmentally damaging (Garrain, *et al*., 2007) (Lim, *et al*., 2008) (Shafiee & Topal, 2009) although other studies contradict these claims (Gärtner & Reinhardt, 2004); (Patel, *et al*., 2003).

The first biopolymers developed for packaging were designed to be degradable and compostable providing alternative end-of-life management options and offering a practical solution to the growing contamination of marine and land environments from plastic litter. More recently the development and promotion of bio-based materials have focused primarily on their renewability and lower carbon footprint compared to their conventional polymer counterparts (Lim, *et al*., 2008), (Shafiee & Topal, 2009). The annual global production capacity of biopolymers is forecast to grow from 0.36Mt (million metric tonnes) in 2007 to 2.33 Mt in 2013, an annual increase of 37% (Shen, *et al*., 2009).

Whilst a number of different types of biopolymers are currently used in packaging, two very distinct categories have emerged. The first category 'Bio-Naturals', made from naturally occurring polymers, are largely biodegradable and have different processing and performance properties to conventional polymers and include polylactic acid (PLA), thermoplastic starch (TPS) and regenerated cellulose (RC). The second category of biopolymers, ‘Bio-Conventionals’, are predominantly synthesized from bio-ethylene, have identical processing and performance properties to their conventional polymer equivalents and include bio-polyethylene (bio-PE), bio-polypropylene (bio-PP) and bio-polyethylene terephthalate (bio-PET). These are interchangeable with their conventional polymer equivalents making them highly attractive to manufacturers, particularly to large multinational companies, as they can be directly substituted for their conventional equivalent without the need to change manufacturing processes, handling methods and recycling processes and systems.

The cost and availability of these bio-conventional polymers has benefited from investment in biofuel production and research, made possible in part due to the commitment of various governments around the world to meet specific targets on renewable fuel use. These mandates include the EU’s Renewable Energy Directive which specifies a 10% renewables content of transport fuels by 2020 and the EPA’s proposal to mandate the blending of 36 billion gallons of renewable fuel into the US fuel supply by 2022 (Biofuels Digest, 2011). This has provided a large and stable market for the production of ethanol, from which ethylene production and subsequent bio-ethylene production can benefit commercially from these economies of scale. In the last 5 years, driven by increasing pressure to reduce CO_2 emissions and improve sustainability, the products and brands using biopolymer packaging has begun to shift from predominantly niche, unprocessed items such as organic fruit and vegetables, to more mainstream global consumer brands such as cola, crisps and chocolate (Colwill, *et al.*, 2009).

However, whilst the development and use of biopolymers gathers pace, the real ecological impacts and benefits of these materials remain uncertain. Life Cycle Assessment (LCA) tools have been used to provide comparisons with conventional polymers, in an attempt to quantify their impacts on the environment. However, published studies are often limited in scope, inconsistent and contradictory, leaving their conclusions open to challenge (Song, *et al.*, 2010). In addition, very little consideration appears to be given to end-of-life management, since it is assumed their biodegradable properties provide inherent ecological benefits and opportunities for conserving resources through the recycling of bio-polymers are rarely addressed.

Often it is simply their ability to be manufactured from renewable resources that is used as the justification for their adoption; however fossil fuels are still expended in the cultivation and harvesting of the feed stock and the extraction and processing of the natural polymers. When other factors such as water and land use, technical performance and End-of-Life (EoL) management are considered, the environmental benefits of these materials becomes more difficult to determine (Tabone, *et al.*, 2010). With the increasing demand from governments, consumers and retailers for sustainable products and packaging, there is a danger that manufacturers may be tempted to make unsubstantiated claims as to the environmental benefits of their products (Green-wash). These claims may encourage the premature adoption of a particular technology or material, which might ultimately not deliver the expected environmental benefits, be fit for purpose or be viable in the long term. This could hinder the development of a more effective and sustainable solutions, whilst increasing the risk of a consumer backlash if these premature claims are later proved to be false or vacuous.

The research assertion made in this thesis is that in order for biopolymers to make a viable and effective contribution to industrial sustainability, the users of these materials need to have a better understanding as to the real impacts and benefits that these materials can provide and more detailed guidance as to the what materials should be used in which applications’. To achieve this consideration must be given as to the company’s expectations of biopolymers, which ones are most likely to meet these expectations, and ultimately what benefits could be achieved, for a particular application, over its whole lifecycle. This highlights the need for a holistic and systematic approach to support the decision making at each stage of the packaging design and development process. Thus the research reported in this thesis has proposed a novel method and tool to support the sustainable design of biopolymer packaging that will provide industry with the means to: rapidly assess the potential strategic benefits of biopolymer packaging within their business; identify the most appropriate materials and suppliers; and to support the comparative assessment of different pack concept and designs. It is envisaged that if such a method is adopted, it will be possible to reduce the overall environmental impact of plastics packaging and reduce our dependence on fossil fuels through the most appropriate selection and application of biopolymers.

The research reported in this thesis therefore aims to extend the scope of existing knowledge on the environmental benefits offered by biopolymers in packaging applications and to provide design support to facilitate the appropriate adoption of these materials for such applications. This will be achieved through;

- Reviewing and assessing the specific environmental benefits offered by biopolymers and defining a method to take advantage of these benefits in packaging applications.

- Developing a novel design support framework and associated prototype tool to assist in the adoption of biopolymers for specific packaging applications such that the overall sustainability of the plastic packaging is increased.

The research for this thesis is structured into three distinct sections: research background and overview, theoretical and experimental research, and research conclusions, as shown in Figure 1.1.

The first section, ‘Research Background and Overview’, provides an introduction to the research, exploring the issues surrounding biopolymers, plastics packaging and eco-design. There are five chapters included within this section; Chapter 1 introduces the subject and provides an overview of the thesis structure. Chapter 2 provides the context for the research explaining the aims and objectives together with a description of the research scope. Chapter 3, 4 and 5 are review chapters, chapter 3 reviews the relevant background to the research, which includes an overview of the main polymers (bio and conventional) used in packaging; their properties, production methods and environmental impacts. Chapter 4 reviews the most common eco-design tools, methods and techniques used commercially for packaging design and assessment. Whilst chapter 5 reviews recent research in LCAs of biopolymer packaging, social assessment methods and multi criteria decision making.

The second section, Theoretical and Experimental Research, consists of four chapters. As well as the development of a general research methodology, a framework for the sustainable packaging design tool is proposed. The specific requirements for the proposed tool are based on an existing understanding of the packaging design process and the findings of the sustainable design tool review. The experimental work commences with the development of three standalone working models for the tool. Simulation tests are conducted for each of the three tool parts or ‘Tiers’ to check their functionality and feasibility. The validity of the overall approach is then tested using case study examples. Chapter 6 outlines the research methodology used in this thesis. Chapter 7 provides a framework for the packaging eco-design tool. Chapter 8 presents the three tiers of the Computer Aided Sustainable Plastics Packaging (CASPPa) design support tool. The tool design and specification, sustainability assessment methodology and metrics used are explained including how the three separate tiers are integration within the tool. Chapter 9 concludes with two case studies to demonstrate the effectiveness of the proposed tool.

The final two chapters of the thesis include the research conclusions and recommendations for further work. Chapter 10 provides a critique of the research carried out for this thesis considering the research contributions made and concluding discussions. Chapter 11 concludes the thesis by identifying the key research conclusions and suggesting further work for the continuation of this research.

Finally, appendices 1 to 5 provide relevant published papers by the author on various aspects of the research reported in this thesis. Whilst appendices 6 to 8 provide additional information used in chapters 8 and 9.

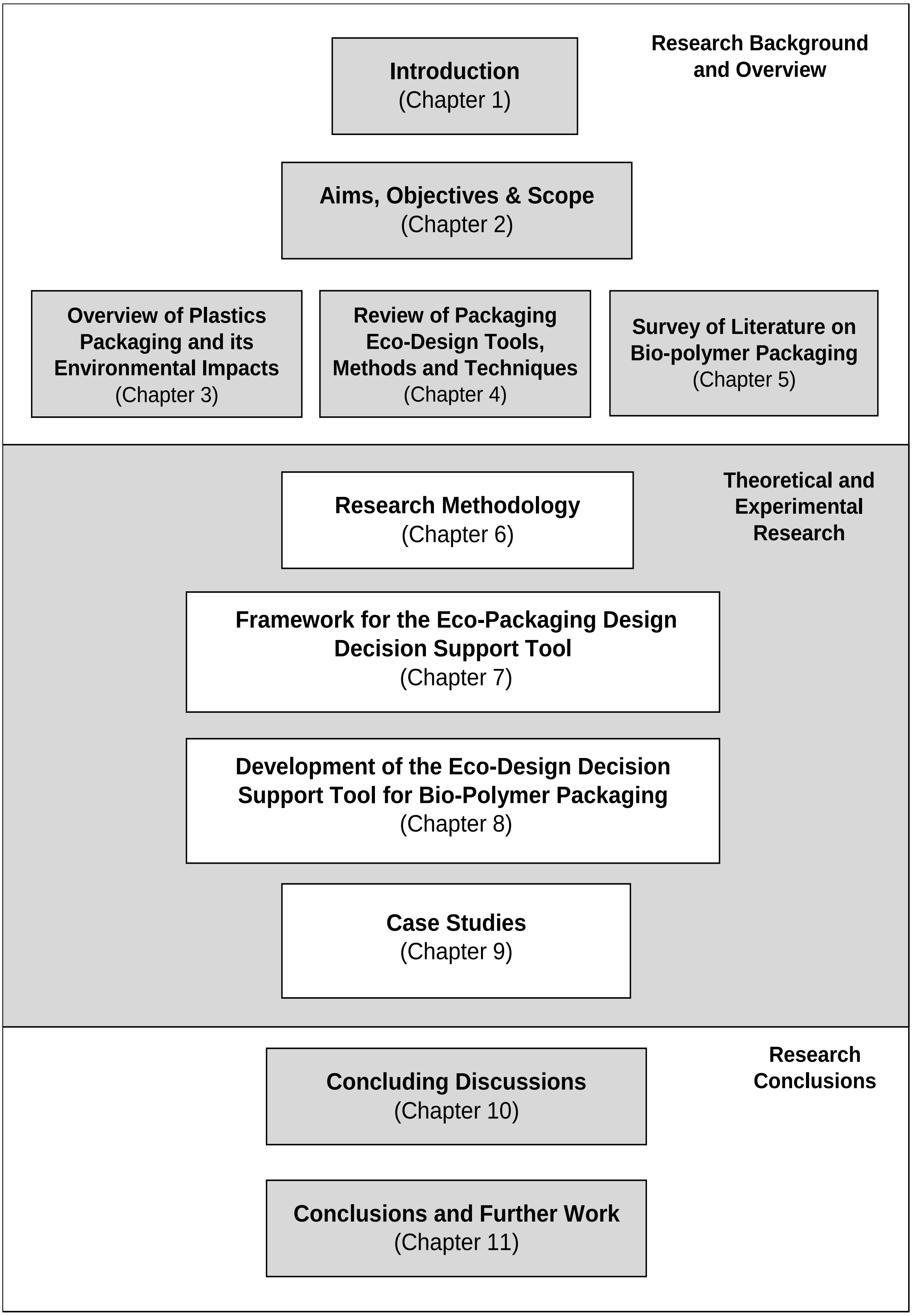


Figure 1-1: Thesis Structure

Chapter 2 Aims and Scope of Research

2.1 Introduction

This chapter describes the aims, objectives and scope of the research reported in this thesis. It begins with a description of the research opportunity, Section 2.2, and goes on to provide the context in which the research is undertaken. The chapter concludes with an outline of the specific scope formed to meet the research objectives.

2.2 Research Context

The use of renewable materials within packaging applications has been promoted as one of the methods to improve the overall sustainability of packaging products. In this context, the global production capacity of biopolymers has been forecast to grow annually by 37 percent, reaching 2.33 Million tonnes by 2013 (Shen, *et al.*, 2009). This rapid growth looks to continue as the markets for biopolymer packaging expand from niche applications of the early adopters for synergetic items such as organic drinks and whole foods, to brand name, mainstream products sold globally such as beverages and snacks. A key driver of this success has been the desire for environmentally friendly, sustainable packaging and the belief that biopolymers meet this requirement. To a large degree this view has been fostered both from the claims made by biopolymer manufacturers, and the emotional attraction by consumers towards a natural, renewable materials. More recently this market demand has been further encouraged by various government initiatives which promote and support the procurement of ‘bio-based’ and ‘sustainable’ products (Skibar, *et al*., 2009).

2.3 Research Questions and Assertion

Unfortunately, the detailed understanding of the environmental benefits from these materials across the whole life-cycle, particularly during their use and end-of-life stages, is inadequate or simply non-existent (Song, *et al*., 2010). This lack of clarity regarding the real benefits of biopolymers as a packaging material highlights the following fundamental research questions that are investigated in this thesis:

- Can biopolymers form part of a company's environmental packaging strategy and contribute towards their overall sustainability goals?
- How do commercially available biopolymer packaging materials perform against each other and their conventional polymer alternatives?
- How should current packaging design approaches be modified in order to accommodate the utilisation of biopolymers in sustainable packaging design?

Therefore the research assertion made in this thesis is that there is a need for a systematic integrated design framework that supports the implementation of biopolymers in packaging applications. Furthermore, the range of technical, environmental, economic and social considerations involved in the adoption of sustainable biopolymer packaging necessitates the development of a decision support tool that provides guidance to businesses at the strategic, tactical and operational levels of the pack design and development process.

2.4 Aims and Objectives

The overall aim of the research is to enable the environmental footprint of plastics packaging to be reduced through the most appropriate selection and utilisation of biopolymers whilst providing companies with a design framework to support their sustainable packaging strategy that meets the future requirements of the business. To achieve this aim the following research objectives have been defined:

a. To review relevant research work and state-of-the-art in biopolymers, life cycle assessments and other published environmental studies including their end-of-life management.

b. To investigate the range of commercial applications of biopolymers in packaging and determine the drivers and barriers to wider scale.

c. To review and assess the range of ‘sustainable and eco’ packaging design and development tools available commercially to identify their shortcomings to support the appropriate adoption of biopolymers in packaging applications.

d. To generate a systematic framework capable of translating and communication the strategic aims and objectives into actionable packaging design requirements.

e. To develop a sustainable design decision support tool to improve the use of biopolymers in plastics packaging applications.

f. To assess and demonstrate the applicability of the research through case studies.

2.5 Scope of Research

The objectives will be achieved by carrying out the following tasks identified as the scope of the research:

2.5.1 *A review of the relevant research work and state-of-the-art in biopolymers, life cycle assessments and other published environmental studies on biopolymers.*

A comprehensive review of literature covering the wide range of issues relevant to biopolymer packaging is required to provide the knowledge with which to direct the initial focus of the research. This will include the properties and production methods of those conventional polymers and biopolymers used in packaging applications, as well as published LCA studies and other environmental data on biopolymers, particularly during their use and end-of-life management stages.

2.5.2 *An investigation into the recent commercial uses of biopolymers in packaging and the drivers and barriers to their further adoption.*

In addition to the general literature review, there is a need to develop an understanding as to the level of adoption that these materials have achieved in different industry sectors. Where possible to review these sectors and quantify their usage in commercial packaging applications in order to gain an insight into which biopolymers might be most likely to achieve widespread adoption as packaging in the future. Both current and future drivers and barriers will be considered as part of this exercise and in addition to the literature review of published academic papers, press releases and company announcements on new product launches using biopolymer packaging will be studied.

2.5.3 *The identification and comparison of the range of relevant design and development tools available for material selection, comparison and specification.*

With packaging being one of the first manufacturing sectors to be targeted specifically by waste legislation, a number of eco packaging design tools are already commercially available. In addition, database tools have been developed which enable the selection of materials, based on performance or properties, for manufacturing. Thus, a review of existing tools and their functionality will enable the demonstration of the novelty of the proposed system and provide useful insights and learning as to the different methods, formats and approaches that can be applied during the development of the new design tool.

2.5.4 *To generate a systematic framework capable of translating and communication the strategic aims and objectives into actionable packaging design requirements.*

This includes the establishment of a methodology to effectively apply data, tools and techniques for the evaluation of biopolymer production, use and end-of-life management within the context of packaging applications. The framework must provide a holistic and integrated approach to the utilisation of biopolymers within new pack development, considering all the requirements of the product and packaging, including the associated environmental and social impacts. In addition to this, it should ideally provide the ability to compare different pack concepts across a range of performance criteria. The various requirements and functions of the pack will be outlined in an initial design plan and further developed into a full design specification.

2.5.5 *To develop a sustainable design decision support tool to improve the use of biopolymers in plastics packaging applications.*

A computer aided decision support tool will be developed to support the implementation of sustainable packaging design framework within commercial applications. Existing LCA data will be used as a baseline for the environmental performance and individual stages of the design process using existing packs as benchmarks will be tested. The performance of the tool will be assessed on a number of criteria such as ease of use, functionality, operation time etc. The final output of the tool will be compared with results achieved using alternative, commercially available, pack development methods.

2.5.6 *Demonstrate the application of the decision support method / tool within the design process.*

Suitable case study products and or companies will be selected to demonstrate the effectiveness of the decision support method or tool in a commercial application. The proposed design framework and tool will be used to firstly identify if biopolymer packaging can contribute to the company’s strategic objectives. If so, then a range of biopolymer options will be identified that meet the design brief/specification. Finally the results of the case study will be used to highlight the wide range of business, technical, and operational factors influencing the design of a biopolymer package.

Chapter 3 Overview of Plastics Packaging, Its Use, Production and Environmental Impacts

3.1 Introduction

This chapter begins with an overview of plastics packaging, its role in modern society, and the resources required for its manufacture. The major polymer types used for packaging are then considered along with their manufacture process. Next, the various forms of plastic packaging, in common usage are reviewed, including their production methods and key applications. Finally the impact of plastics packaging on the environment is considered and the potential for biopolymers to become an environmentally friendly alternative are discussed.

3.2 Plastics Packaging and its Role in Modern Society

"Packaging is an integral and essential part of the industrial and commercial supply chain. It protects goods from damage, allows efficient transport distribution, offers convenience, prolongs shelf-life, enables easy use, informs the consumer and helps to promote goods in a competitive market place." (INCPEN, 2012)

With the world population forecast to increase to over 9 billion by 2050 (Figure 3-1) (combined with the steady increase in global per capita incomes over the same period (Godfray, *et al*., 2010) the demand for agricultural crop production, for food and feed, is projected to double from 2005 levels accordingly (Tilman, *et al*., 2011).

Packaging plays a key role in food distribution, helping reduce loss and wastage from spoilage and damage. It is widely acknowledged that without packaging, food loss would be significantly higher; for example in developing countries without sophisticated distribution and packaging systems, as much as 50% of the food produced will never reach the consumer (INCPEN, 2010). Furthermore, it has been calculated that on average, the energy use to produce the food is on average ten times greater than the energy required to make the packaging used to preserve it (Kooijman, 1994).

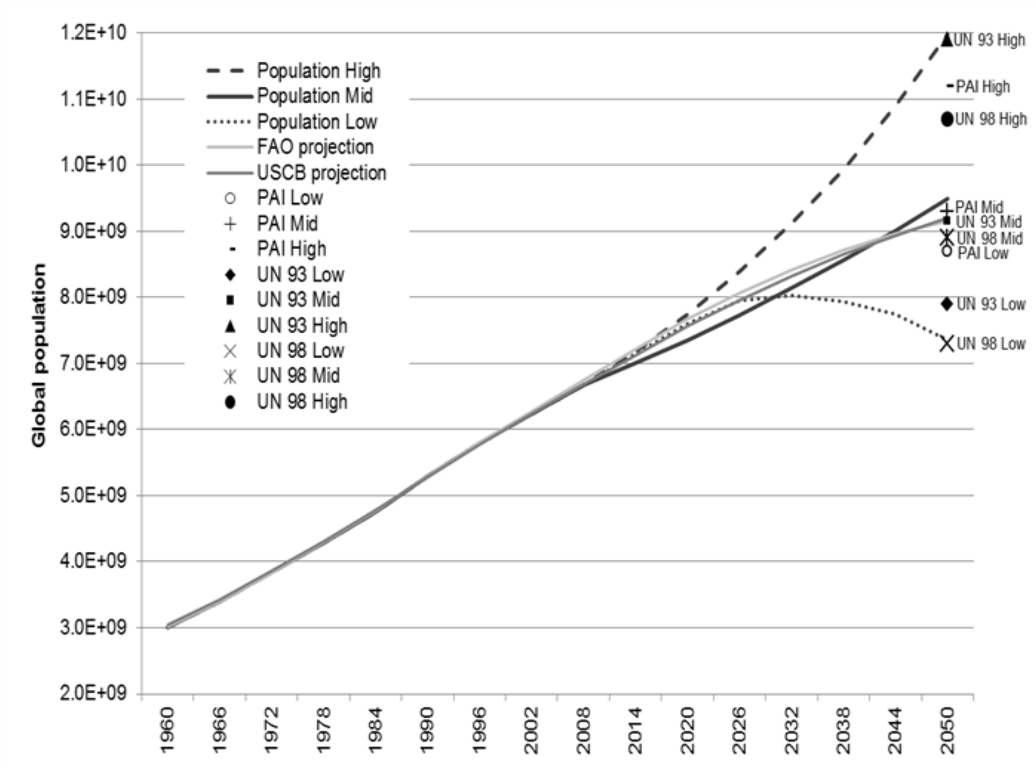


Figure 3-1: Projections for global population growth to 2050. (Colwill, et al., 2012)

In 2011 a report commissioned by the UK Government identified ‘the need to reduce food wastage’ as one of the key strategies for meeting the future challenges of global food security and sustainability. This report concluded by acknowledging that the use of modern packaging was one of the key mechanisms for meeting these future challenges (Foresight, 2011).

3.2.1 *Packaging: Function and Need*

The industry reference book ‘Fundamentals of Packaging Technology’ describes the four essential functions that packaging is generally required to perform as to: contain, convey, protect/preserve and inform/sell the product (Soroka, 2002). Within each of these functions there will be additional product, manufacturer, distributer, retailer and customer requirements essential or desirable that should be met.

Figure 3-2 provides an overview of some of the more common of these, although in practice these are likely to be more complex and numerous than shown.

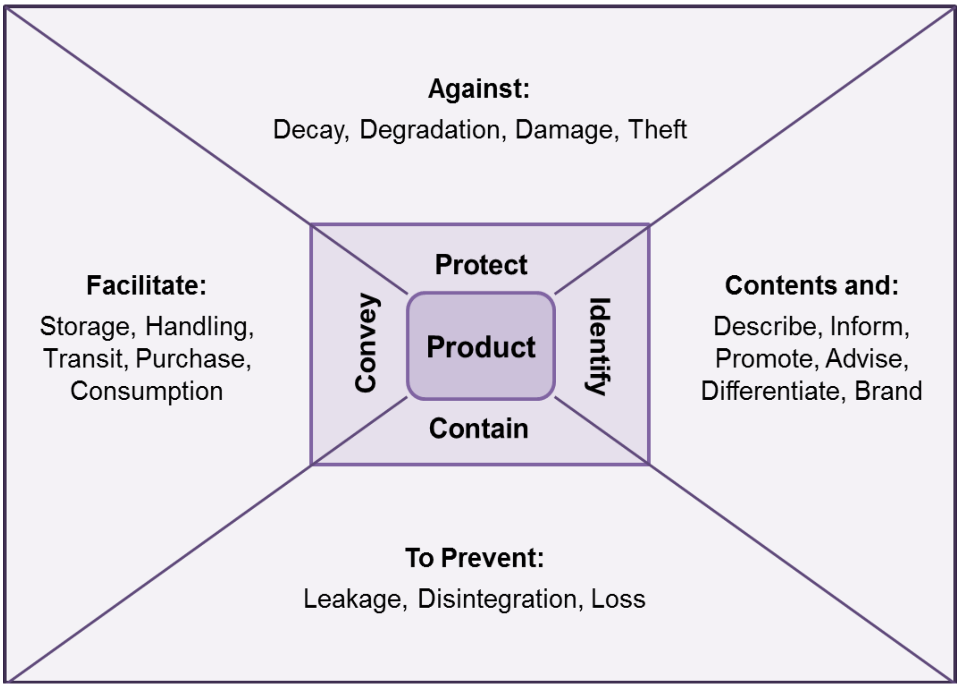


Figure 3-2: Diagram showing the four essential functions of a package with examples of the common functional requirements of each. Adapted from (Stewart, 1994).

A typical packaging specification for example, that details all the essential and desirable pack performance requirements, can run to many pages and will require the input from most of the different departments within an organisation. A typical packaging specification for a plastic bottle is provided in appendix 6.

Plastics have become one of the most important and widely used packaging materials, due to their favourable properties, versatility and affordability. Since their discovery in the mid 20thcentury, the production and use of plastics has grown rapidly, dominating the consumer packaging sector.

When plastics were first produced however, they were far too expensive to be used for ‘low value/disposable’ applications such as packaging. In 1950 the global production of plastics was approximately 1.5 million tonnes (Plastics Europe, 2012). However, after the end of the Second World War, production rapidly increased such that by the end of the 20th century annual production had grown to 160 million tonnes per year and the cost had fallen to make it competitive with other packaging materials (Packaging Today, 2011).

The global production and consumption of plastics for packaging has continued to grow at around 5% per annum, despite several global recessions and various initiatives to reduce the amount of materials used per pack (Plastics Europe, 2012). Plastics packaging is therefore important not just for food preservation but as an integral part of our modern urban lifestyles and its use has been forecast to grow even in the most conservative projections (Figure 3-3).

A key driver for this growth will come from increased consumerism and general lifestyle trends. As global populations increase and become more urbanised and wealthy, so the need for modern packaging methods and systems to meet the demands of increasingly sophisticated supply chains, will also grow.

It has been estimated that by 2050 there will be 6.3 billion people living in urban areas, accounting for approximately two thirds of the world's population. This is an increase of 100% from 2005 levels and is occurring mainly in the emerging economies such as India, Africa and China (United Nations, 2012).

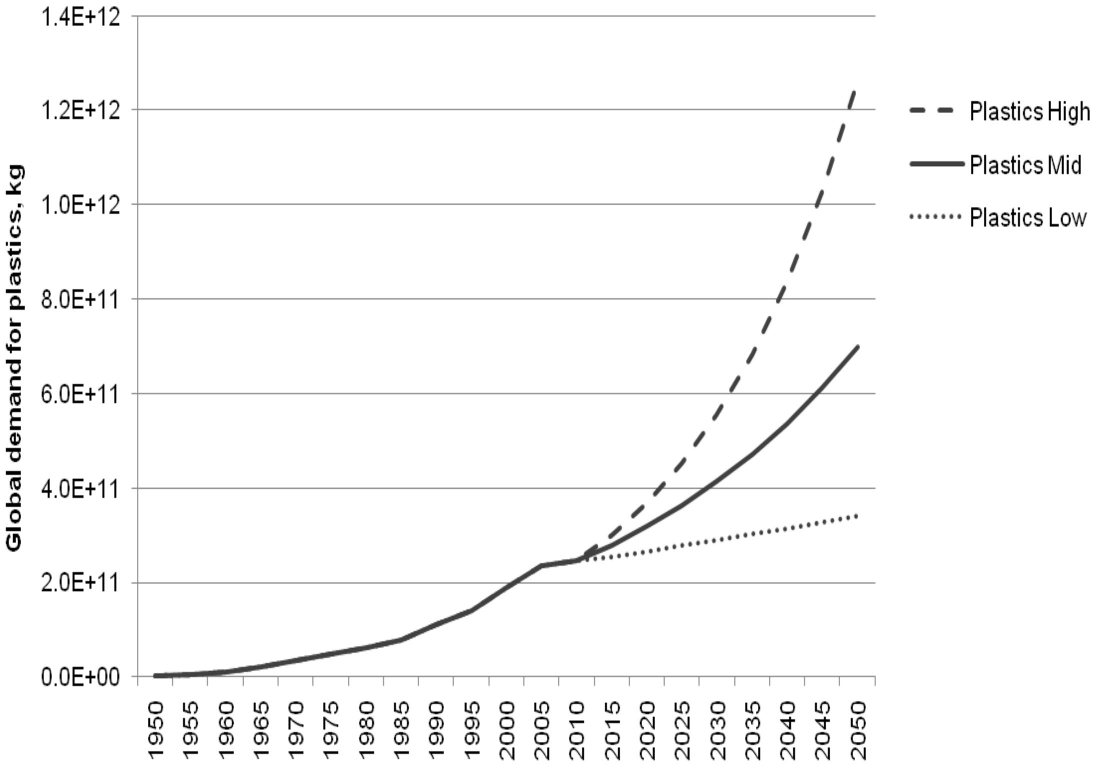


Figure 3-3: Global demand for plastics, projected to 2050. (Colwill, et al., 2012)

It is therefore reasonable to predict that the demand for packaging will also continue to increase, as will the materials from which it they made, particularly when its value as an essential component of an efficient, secure and sustainable supply chain, rather than a wasteful luxury, is fully recognised and understood.

3.2.2 *The Pros and Cons of Plastics as a Packaging Material*

The growth in the use of plastics as a packaging material has largely been driven by the many benefits that it offers to a wide range of packaging applications. Food for example is one sector where the use of packaging has significantly reduced the amount of spoilage caused by moisture loss, bacterial contamination or oxidation. In the past 50 years, the UK's food waste has been reduced from nearly 50 percent to less than 3 per cent (INCPEN, 2010). Of course plastics are not the only material that has contributed to this improvement, glass, steel and aluminium all have excellent barrier properties and have been used widely as packaging materials (Soroka, 2002).

Plastics however have a key advantage over these other materials due to their weight to strength performance, resistance to impact (denting and shattering) and ease of processing (Plastics can be delivered as loose pellets or reeled sheet/film and processed 'in line' to form a container as part of the filling/packing process). Recent case studies, provided by members of the flexible packaging association, have shown that plastic pouches, compared to other pack formats such as cans and glass jars, can save over 95% in pack weight without loss of shelf life. Plastic jars can also reduce material weight by as much as 90 per cent compared to their glass counterparts (American Chemistry Council, 2009)

In addition to this comparative performance, the average weight of plastic packaging in general has decreased by nearly 30% in the past 10 years (WRAP, 2008). Drinks, particularly carbonated soft drinks, are now almost universally packaged in plastic bottles. In addition to offering high speed in-line forming and filling advantages, they are significantly lighter than their glass equivalents. Another key advantage is their handling and safety benefits compared to glass, which can shatter thus becoming a contamination and potential injury hazard.

Whilst the barrier properties of plastics are generally not as good as metals or glass, the careful selection and combination of polymers can reduce gas and moisture permeability significantly whilst the use of treatment techniques, such as metallisation, foil layers or inorganic coatings, can increase this significantly whilst adding protection from UV (Soroka, 2002). Plastic coatings are also used to protect metal cans from acidic attack, to strengthen glass and to make paper and board more water resistant. On average only 1%-3% of the weight of a packaged product comes from the plastic packaging (INCPEN, 2010).

Another major benefit of plastics is their design and manufacturing flexibility, allowing complex devices and mechanisms to be incorporated into everyday products e.g. ‘draught’ widgets in beer cans, child resistant closures, tamper evident seals, delivery devices and dosing mechanisms. Plastics have even enabled the packaging to equal the product in the consumer’s purchasing decisions, such as with Kinder Surprise™ chocolate eggs, mints in dispensing packs and other consumer products, where the packaging adds value or provides additional consumer functionality. Although total plastics production only accounts for around 5 percent of the world’s total crude oil consumption (Quieroz & Collares-Quieroz, 2009) and that used for packaging is a fraction of this again, about 38% (British Plastics Federation, 2009) it has become one of the more visible symbols of consumer excess, and omnipresent in our daily lives.

It is not surprising then that plastics packaging has attracted so much attention from consumer groups, governments and environmental activists, and yet despite the legislation, campaigning and industry initiatives to reduce, recover and recycle, plastics packaging use has continued to grow. To a degree, plastics have been a victim of their own success, for the reasons already discussed (e.g. cost, versatility, weight, strength). However, there are three main concerns associated with the continued use of plastics in packaging application:

1. Fossil fuels are a finite resource and will eventually be exhausted or become too expensive to use in many of the current applications.

2. As demand continues to outstrip supply, so exploration and extraction will move into increasingly difficult and environmentally sensitive areas, becoming costlier, riskier and potentially more environmental damaging to extract.

3. The uncontrolled disposal of plastic packaging into the environment is both unsightly and damaging and can be particularly hazardous to wildlife through entanglement, ingestion or toxicity.

Furthermore, whilst all commonly used thermoplastics can be recycled, the reality is more complex. Many plastic packages are made from a mixture of different polymers which are problematic to separate, making them difficult to recycle at End-of-Life. Packaging made from a single polymer type, such as a plastic milk bottle, are much easier to recover using simple mechanical based recycling technologies. Theoretically the limit for recycling polyethylene is around six times, as the polymer becomes slightly degraded each cycle (Bakker, 1986). In reality however, recycling rates are still relatively low, so new virgin material entering the system dilutes the recycled material so avoiding quality issues from the build-up of degraded polymer in the system.

Where it does not make economic or environmental sense to recycle a polymer, then the energy can be recovered through incineration or gasification. Used plastics have a higher calorific value than coal and can provide an affordable local energy supply. In Europe recovery of used plastics reached 50% in 2006 and this is increasing due to new legislation setting higher recycling targets and improved infrastructure and consumer education (WRAP, 2008). However despite these measures, the recycling and recover of polymers makes only a minor impact on the rate of fossil fuel consumption. Clearly alternatives are needed to preserve these precious resources for future generations and ensure that their current use and disposal is environmentally sound.

3.3 Overview of Polymers Used for Packaging

Polymers are used extensively by industry across a variety of sectors from food to furniture, construction to consumer goods, however it is the polymers used in packaging that are the focus of the research in this thesis, and these are predominantly thermoplastics. The following section considers the various sources of these polymers and how they are manufactured and converted into the raw materials for plastics packaging.

3.3.1 *Sources of Polymers*

The majority of plastics used in packaging today are synthesised from fossil fuels such as crude oil, natural gas and to a lesser degree coal. This has not always been the case; prior to the discovery of manufacturing plastics from fossil fuels, the majority of plastics available were produced from natural materials, such as cellulose from plants; Cellophane, made from wood cellulose, was for many years a popular packaging film used for wrapping a wide range of consumer goods. By the 1980's however, its use had been largely substituted by these new 'conventional polymers' made from fossil fuels.

3.3.1.1 Conventional Polymer Feedstock

The three main sources of feedstock currently used for manufacturing the majority of conventional polymers are crude oil, natural gas and coal. These 'fossil fuels' are termed non-renewables because, whilst they are formed from organic matter, the timescales required for this formation (millions of years) are too large to be replenished within human timeframes.

Crude Oil is formed from organic matter that has been deposited over millions of years becoming increasingly covered with sand and silt. Over long periods of time it is subjected to intense heat and pressure under anaerobic conditions, which eventually leads to the formation of complex chains of repeating hydrocarbons. Crude oil varies in grade, depending on the fractions of different elements contained in it. Terms such as light, sweet and heavy are used to describe its quality, as are references to its geographical origin (e.g. Brent crude).

Other forms of grading include the A-D classification used by the Environmental Protection Agency. This is based on physical characteristics of the crude and its particular impact on the environment in the event of a spill (EPA, 2011). The majority of crude oil is used to produce transport and heating fuels, only around 4% is used as a feedstock for plastics. Figure 3-4 shows the main products produced from a barrel of crude oil. On average a 42-U.S. gallon barrel of crude oil yields about 45 gallons of petroleum products largely due from volume based processing gains (Energy Information Administration, 2009).

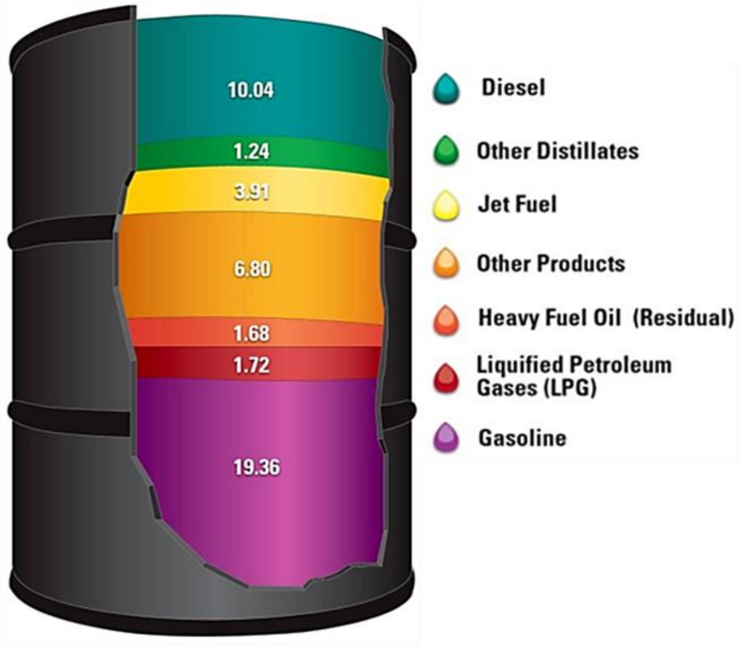


Figure 3-4: Products made from a Barrel of Crude Oil. Source: (Energy Information Administration, 2009).

Natural gas, like oil and coal was formed from the remains of plants and animals and is therefore often found with these other fossil fuels. Unlike coal and crude oil, natural gas is relatively clean burning and emits lower levels of harmful by-products into the atmosphere per unit of energy produced. Natural gas is colourless, odourless and tasteless which makes detection of leaks difficult, therefore when other chemicals are sometimes added to it, which give it a distinctive ‘detectable’ smell. Natural gas is a major feedstock for plastics.

Coal was formed over a million years ago from plant matter that accumulated in wet conditions (marshes etc.) and became buried by silt and sand (Figure 3-5). This is a gradual process involves involving firstly the formation of peat followed by different grades of coal usually becoming blacker and harder as it matures (University of Kentucky, 2012).

Coal is one of the easiest of the fossil fuels to store and transport being stable and non-volatile at normal temperatures. However coal is also one of the dirtiest of the fossil fuels, particularly the less mature ‘brown’ deposits. Whilst plastics can be made from coal, it is not a preferred feedstock, used mainly when other feedstocks are unavailable.

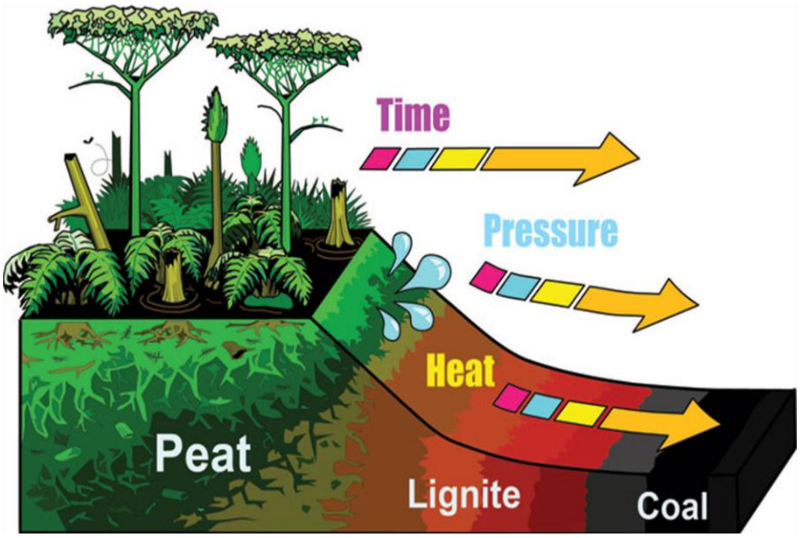


Figure 3-5: How Coal is Formed. Source: (University of Kentucky, 2012)

3.3.1.2 Renewable Feedstock for Biopolymers

Polymers in nature are generally produced and used as a structural building material such as cellulose and lignin in plants and keratin in animals, or as a store of energy, e.g. sugars and starches in plants and fats and lipids in animals. These materials are sometimes by-products of normal food production (potato starch), whilst other materials compete directly (corn, sugarcane). Sugars and starches, currently the main feedstock for the production of the majority of biopolymers used in packaging, are one of the most important food groups in the human diet either directly (potatoes, rice, fruit etc.) or indirectly (meats, breads and snacks). Table 3-1 provides a summary of the main feedstock used for biopolymers. Further consideration will now be given to the types of feedstock used to produce these intermediate materials (e.g. starch, sugars, cellulose and oils), which are subsequently used to manufacture biopolymers.

Table 3-1: Main sources of feedstock for biopolymer packaging production

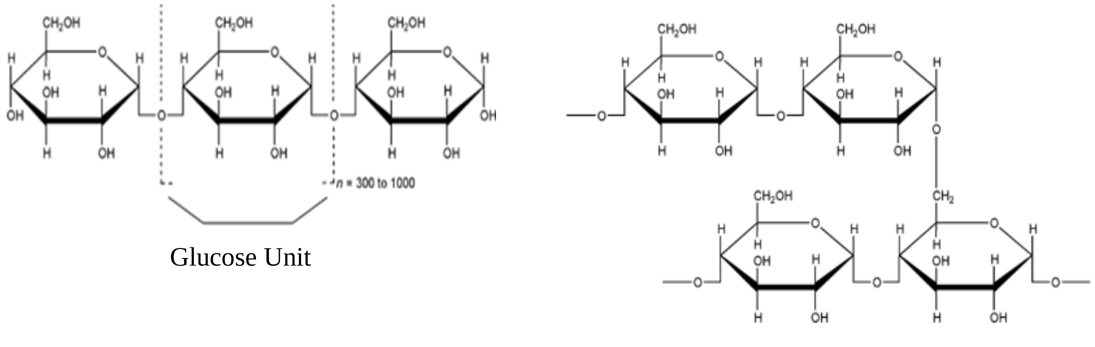
General Category	Category Examples	Structural Materials	Storage Materials
Organisms	Bacteria		PHA/PHB
Plants	Cereal Crops (Wheat, Maize) Root crops (Potato, cassava) Sugar cane and beet Seed crops (rapeseed) Woody Plants (trees)	Cellulose and Lignin	Starches Starches Sugars Oils
Animals	Waste products Milk	Keratin, Casein	Oils, fats & waxes

Starch is currently one of the most widely used feed stocks for the production of biopolymers. This polysaccharide may be used directly, for the production of starch-based plastics, or broken down to provide a source of sugars. The extracted starch comprises of a mixture of up to two different polysaccharide components, amylose and amylopectin (

Figure **3-6**), the former has a linear molecular structure, whilst the latter is highly branched (Salmela, 2006). The principal sources of starch include cereals, roots and tubers. These vary in the amount of starch present and in the concentrations of the different types of molecules present, amylose and amylopectin, which affect the physical and chemical properties of the starch.

Table 3-2 provides statistics for the global production of starch from various feedstock. It shows that the USA derives almost all of its starch from maize (corn), whereas in Europe corn, wheat and potato are the important starch feedstocks. Outside of these two regions, whilst maize remains an important crop, the majority of starch production is obtained from cassava or tapioca. Whilst other sources include rice, barley and sweet potatoes (LMC International Limited, 2002).

Cellulose and Lignin are the most abundant organic polymers on earth. Cellulose accounts for approximately 33 percent of all plant matter, although wood and cotton have higher concentrations 40-50 percent and 90 percent respectively, whilst lignin is found mainly in the woody and vascular tissues of plants. Lignin accounts for around 25 – 30% of the dry mass of wood. (Harmsen, *et al.*, 2010). Cellulose has been used as a packaging material either as ‘cellophane’ (a brand of cellulose film) and rayon (fibres used in textiles), known collectively as ‘regenerated cellulose’.



a) Amylose

b) Amylopectin

Figure 3-6: Structure of the two polysaccharide components of starch (Salmela, 2006)

Table 3-2: Global production of starch in 2000 in million tonnes (LMC International Limited, 2002).

	Maize	Wheat	Potato	Other	Total
EU	3.9	2.8	1.8	0.0	**8.4**
US	24.6	0.3	0.0	0.0	**24.9**
World	39.4	4.1	2.6	2.5	**48.5**

Cellulose is also being investigated as an alternative feedstock for biopolymer and ethanol production. This would allow the agricultural waste from food crops to be used or alternatively the use of non-food crops such as hemp, switch grass, willow and poplar plant species (Bullis, 2007).

Lignin is found mainly in compression wood and less so in tension wood. Pulp with high lignin content is used to make high yield/strength papers such as newsprint, but lignin rich paper is susceptible to yellowing with age. Lignin has also been converted into a polymer material called ‘Arboform’, which has similar properties to those of injection moulded synthetic plastics (Tecnaro GmbH, 2000).

Plant Oils: The most common crops grown for oils in Europe and the US are rapeseed and soybean which account for about ninety per cent of production. Oil can also be obtained from castor, Jatropha, flax, sunflower, palm oil, coconut and hemp. Castor oil is one of the most widely used plant oils in industrial applications due to its naturally occurring hydroxyl groups on its fatty acid chains. Other vegetable oils, which have been chemically modified to add hydroxyl groups, are also used in the production of polyurethane and are the primary raw materials for the production of sebacic acid, the base ingredient for nylon production (Troughton, 2008). Nylon has many industrial uses however it’s as a high strength/barrier film that it most widely used in packaging.

Sugars: Approximately 80% of the world’s sugar (sucrose) is produced from sugar cane, whilst the remaining 20% comes largely from sugar beet. Brazil is the world’s largest sugar producer, accounting for 25% of global production, and one of the world’s largest manufacturers of bioethanol. Sucrose is the most widely used sugar commercially, 165 million tonnes in 2012, although other sugars such as fructose and glucose have some commercial applications. High-fructose corn syrup (HFCS), which has seen a significant increase in use within western markets, is used mainly in food production (Sucres et Denrees, 2012).

Biopolymers produced from sugars, at a commercial level, have emerged largely from the development of biofuels (bioethanol). Bioethanol is mainly produced from the fermentation of sugar, although starch and cellulose have also been investigated as alternative feedstock. The ethylene produced from this bio-ethanol can then be polymerised into polyethylene or further processed and used to manufacture Bio-PET.

Bio-PET is made from mono-ethylene glycol (MEG) and purified terephthalic acid (PTA). Ethanol derived from sugarcane will be fermented to create the bio-MEG. This has the advantage over other biopolymers in that it is directly interchangeable with conventional PET. Coca-Cola's goal is to develop feed stocks suitable for 100% bio-based PET for their packaging (Coca-Cola Company, 2013).

3.3.1.3 Waste as a Feedstock

A feedstock that has attracted significant research interest in recent years is organic waste. Waste is produced at various stages in the supply chain from agriculture through manufacturing to post consumer, how usable and scalable the use of this waste is depends on the type of ‘waste’ and processing technology used. Most production processes, including agricultural ones, are generally optimised towards minimising waste and maximising output. So whilst cereal crops are grown primarily for their seeds, the rest of the plant still has other potential uses, one of which is to return carbon back to the earth and maintain soil quality (composting). However, the ability to produce biopolymers from these ‘waste’ materials could help reduce biopolymer competition with food production and may even eliminate it.

Another source of bio-waste is ‘post-consumer waste’ which is currently collected either separately or mixed in with other household waste such as plastics packaging, food waste, papers etc. Whilst there are a number of recycling and recovery methods available to deal with this waste, a large proportion still goes to landfill. Using it as a feed stock has multiple benefits including: reducing the amount of waste going to landfill; reducing methane gas emissions from landfill; reducing the demand for virgin materials; and providing a ‘green’ source of alternative energy (DEFRA, 2011).

It is not just solid municipal wastes that can be used as a feed stock, naturally occurring microbial processes have been developed to convert carbon found in organic wastewater in to polyhydroxyalkanoates (PHA); a family of high-performance biopolymers with excellent properties suitable for a wide range of industrial applications. These bio-refineries consume carbon and other nutrients from waste streams, greatly reducing sludge waste, chemical treatment, incineration, and disposal costs (UC Davis, 2009). Algae, grown using waste materials such as sewage, is also a potential source of oil and can be cultivated without displacing food production. Similarly, oil from halophytes such as *salicornia bigelovii*, can be grown using saltwater in coastal areas where general food crops cannot be grown, thus not displacing conventional food production (Weber, *et al.*, 2007).

Waste vegetable oil is widely used to produce biodiesel, but since the available supply is significantly less than the amount of petroleum-based fuel that is required, this solution does not scale well. Likewise researchers at the University of Nevada, Reno, have successfully produced biodiesel from oil derived from used coffee grounds. Once extracted, the oil underwent conventional processing into biodiesel and it was suggested that around several hundred million gallons of biodiesel could be made annually. However, even if all the coffee grounds in the world were used to make fuel, the amount produced would be less than one per cent of the diesel used in the United States alone (Schill, 2009).

3.3.2 *Polymer Classification*

The majority of plastics used for packaging materials are thermoplastic, this means they can repeatedly be softened and hardened by raising or lowering their temperature accordingly. This property allows the plastic to be easily and cheaply formed into shapes and films, heat sealed and eventually recycled/reused, which is one reason why plastics are so widely used as a packaging material. For the purposes of this thesis we will consider the classification of conventional and biopolymer thermoplastics separately.

3.3.2.1 Conventional polymers

The term conventional polymer is used to identify a polymer that has been derived from fossil fuels; Crude oil, Natural Gas and Coal. These can be broadly categorised into thermoplastics and thermosets, which can then be subdivided further into plastics, elastomers, structural foams and polymer alloys as shown in

Figure **3-7** (Edwards, 1998). Approximately one third of all the conventional polymer plastics manufactured are used for packaging and these are predominantly thermoplastic. There are many grades and blends of different thermoplastics used in packaging, however there are just five main polymer groups that account for over 95% of the annual global usage: Polyethylene (PE), Polypropylene (PP), Polyvinyl Chloride (PVC), Polystyrene (PS) and Polyethylene Terephthalate (PET).

A breakdown of the main thermoplastic polymers used for packaging is shown in Figure 3-8. Percentages given are based on the value of the polymers sold in 2008, based on dry weight comparison, except for phenolic resins which are reported on a gross weight basis (American Chemistry Council, 2009). This clearly demonstrates the importance of certain polymer types such as PE, which is subdivided into low density PE (LDPE), linear low density PE (LLDPE) and high density PE (HDPE). However, it does not necessarily show the complexity of the different polymer blends, laminates and composites that are used in the packaging industry.

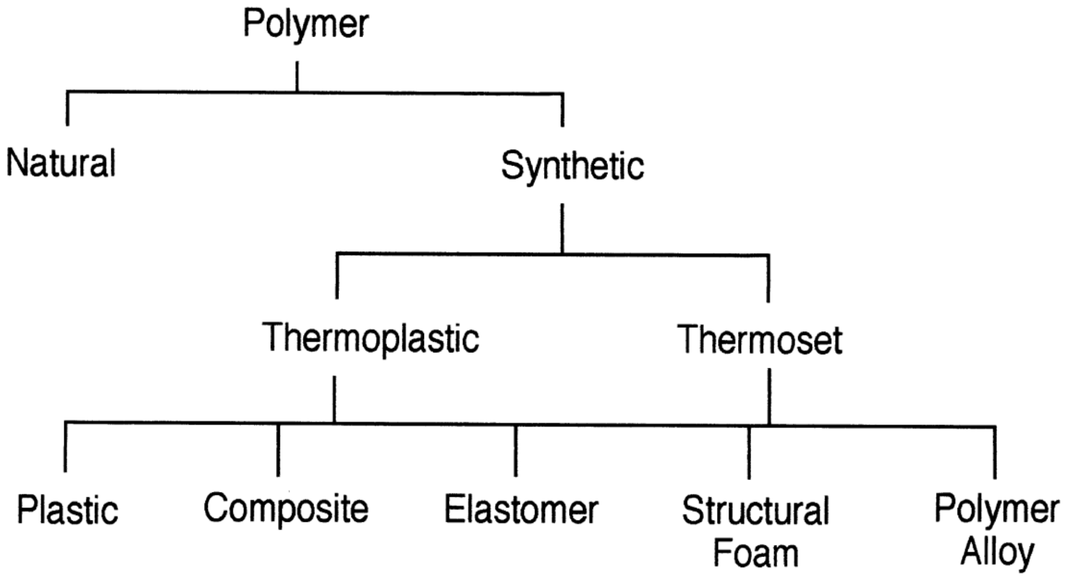


Figure 3-7: Classification of Polymers (Edwards, 1998)

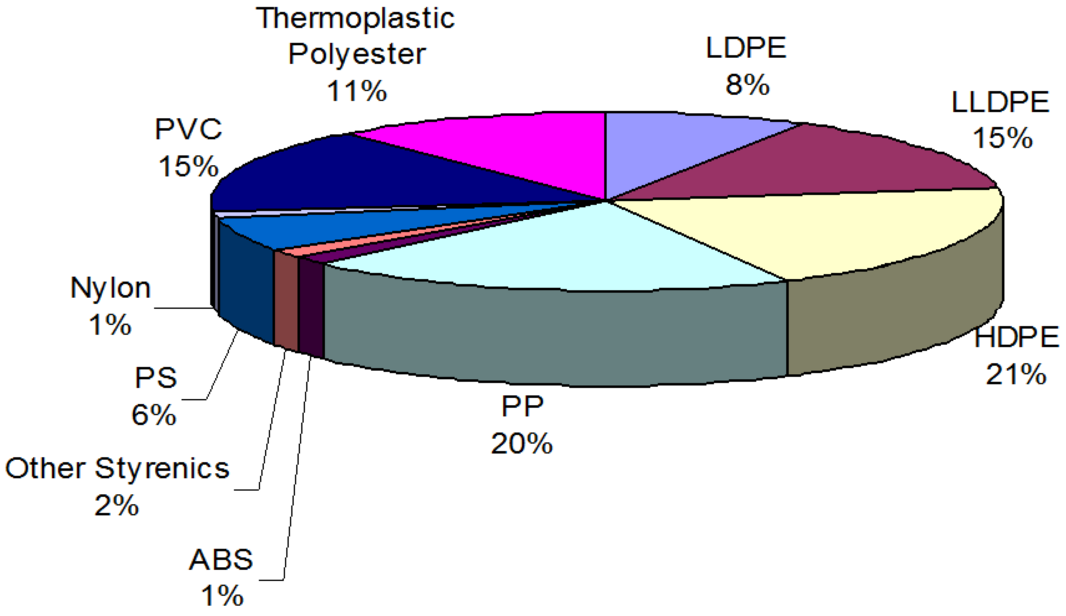


Figure 3-8: Thermoplastic polymer sales & captive use in 2008, Source: (American Chemistry Council, 2009).

3.3.2.2 Biopolymers

The first biopolymers to be used commercially were produced from starch, cellulose and natural oils such as linseed. These were followed by a second generation of biopolymers such as Polylactic Acid (PLA) and PHA, which having similar processing and aesthetic properties to conventional plastics, could replace conventional polymers across a wider range of formats such as bottles, trays and other moulded products. More recently a third generation of biopolymers were developed, launched commercially in 2007, which have identical properties to their conventional polymer equivalents. These include bio-PE and bio-PET which can be directly substituted conventional PE and PET accordingly, and have been quickly adopted by major brand owners as the preferred biopolymer option (Van de Velde & Kiekens, 2002) (Crank, *et al*., 2005).

Depending on the original bio-source and the extraction / production process used, a number of various classifications for the different biopolymers have been proposed. One such classification for biodegradable polymers, proposed by Prof. Luc Avérous, (Avérous, 2007), suggests four categories, however only three are obtained from renewable resources the fourth being a conventional polymers with additives that speed their bio-degradation. This fourth category is not considered to be a biopolymer under the definitions used within this thesis.

The different biodegradable polymers were further classified into two main families; the agro-polymers and the biodegradable polyesters, of which there are two types as described below in points (2) and (3), (Avérous, 2007),

The different types of biodegradable polymers as classified by Avérous are:

(1) Polymers from biomass such as the agro-polymers from agro-resources (e.g. TPS and RC).

(2) Polymers obtained by microbial production, (e.g. PHA).

(3) Polymers conventionally and chemically synthesised and whose monomers are obtained from agro-resources, (e.g. PLA).

This categorisation was later adopted by Maya and Sabu (2008) in their paper 'Biofibres and biocomposites', and presented in diagrammatic form, as illustrated in Figure 3-9. (Maya & Sabu, 2008).

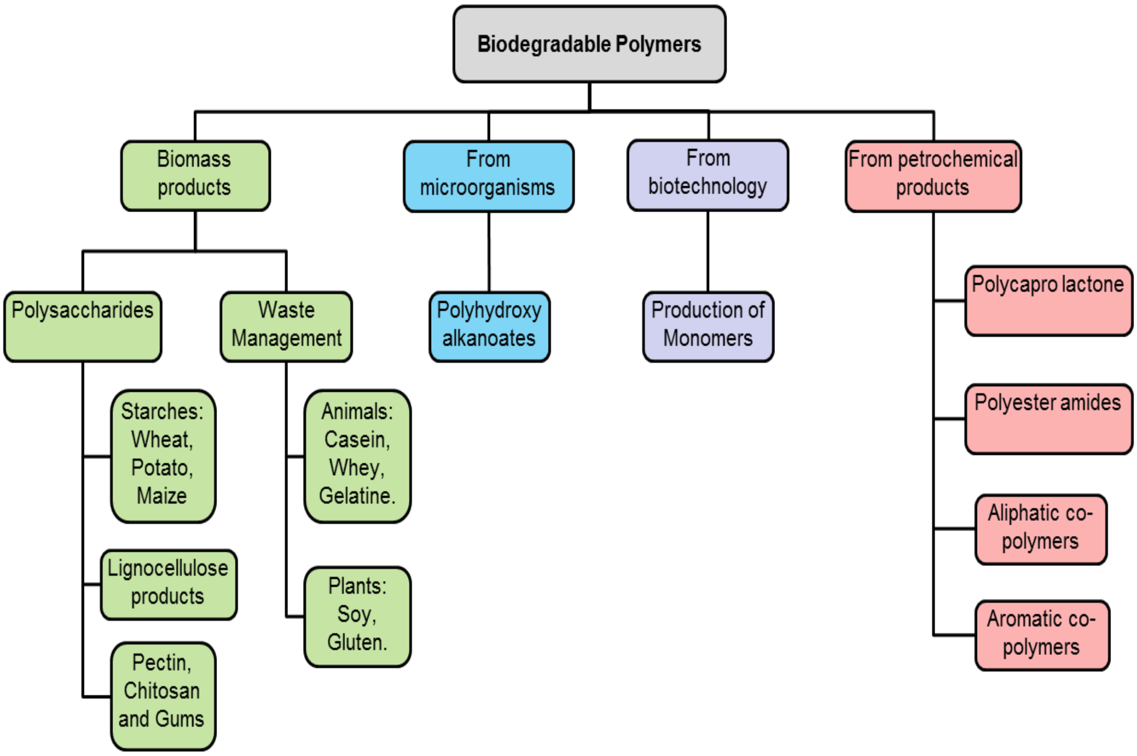


Figure 3-9: Classification of the biodegradable polymers, (Maya & Sabu, 2008).

Quieroz and Collares-Quieroz (2009) provide a similar but alternative overview of the principal polymers originating from renewable sources. Figure 3-10 summarises the three main classifications of biopolymers. Firstly, naturally-occurring polymers may be extracted directly from biomass sources and modified to produce plastics. The polysaccharides, starch and lignocellulose, are the most common naturally-occurring polymers to be used in the production of plastics.

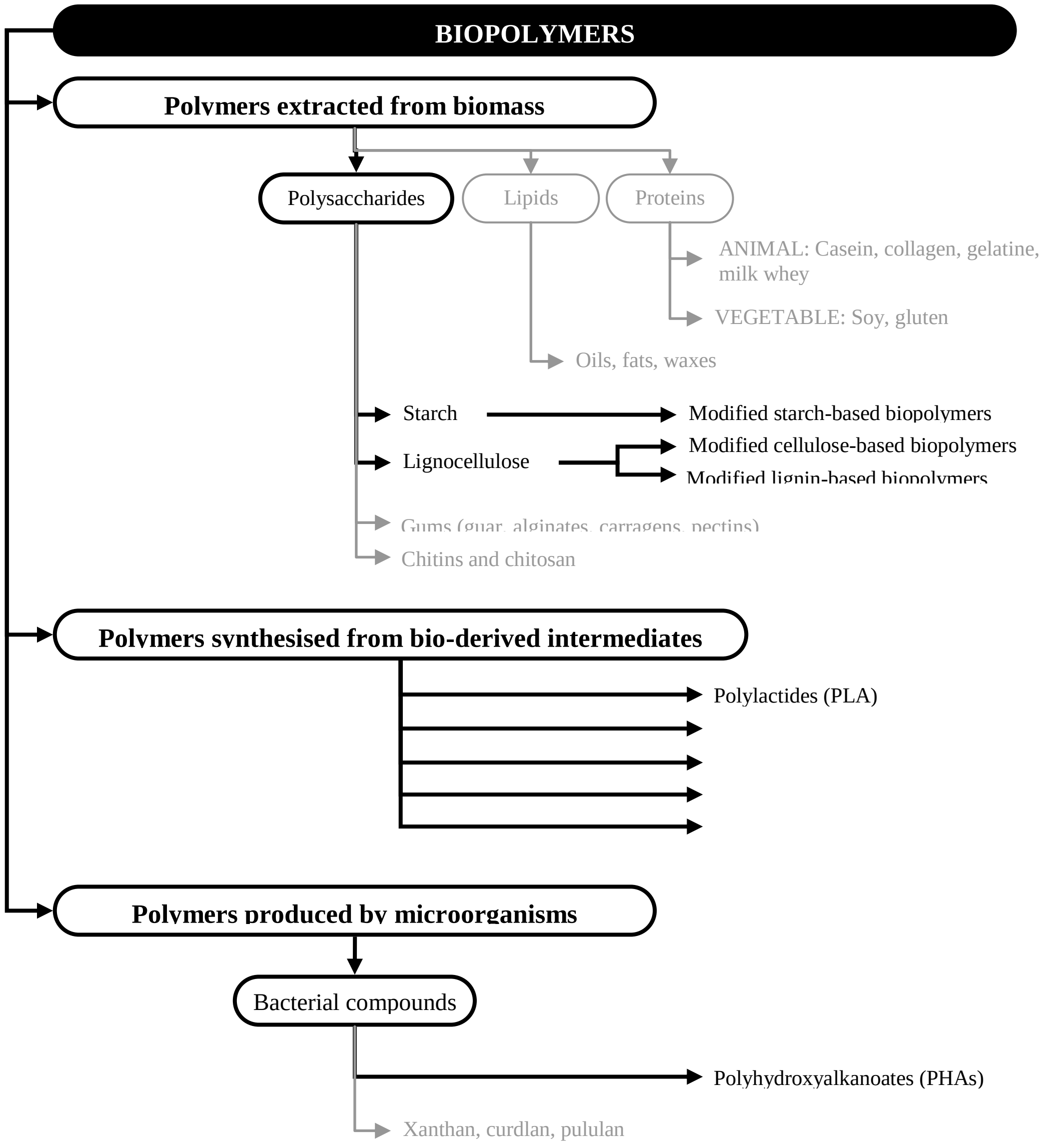


Figure 3-10: Overview of principal biopolymers, adapted from (Queiroz & Collares-Queiroz, 2009). Flows in bold indicate routes to the principal bio-plastics.

Secondly, biopolymers may be produced from bio-derived intermediates. For example Polylactic Acid is produced from lactic acid, derived from dextrose. Bio-polyethylene is an example of a conventional plastic which, when produced by the polymerisation of ethylene derived from bio-ethanol, can be considered as a biopolymer.

Thirdly, biopolymers may be produced by microbiological processes, either in the natural environment, or under synthetic conditions e.g. Polyhydroxyalkanoates are a family of plastics produced in this way. In Figure 3-10, the principal biopolymers used in the production of plastics are indicated by bold flows. Other biopolymers, shown in grey, are not currently used in the commercial production of plastics for packaging.

The British Plastics Federation (BPF) proposes a simpler two category classification (British Plastics Federation, 2009):

"Natural bio-based polymers: are synthesised by living organisms, essentially in the form in which they are finally used. After extraction and purification, direct industrial exploitation is possible. Examples of naturally produced bio-based polymers include; polysaccharides, cellulose, starch, proteins and bacterial polyhydroxyalkanoates".

"Synthetic bio-based polymers: whose monomers are derived from renewable resources but which require a chemical transformation for conversion to a polymer. Many conventional polymers can, in principle, be synthesised from renewable feedstock. For example, corn starch can be hydrolysed and used as the fermentation feedstock for bio-conversion into lactic acid from which polylactic acid can be produced through chemical processing. Although its origin is renewable, the polymer cannot be considered 'natural' as it is synthesised within a chemical plant".

These classifications however are based on the origin and processing of the polymer and do not consider the polymers final properties. Therefore an alternative classification system is proposed in this thesis that considers the whole life cycle of the polymer in terms of its source, production, use and end-of-life. This gives four primary classification groups based on their derivation and degradability as shown in Table 3-3.

Table 3-3: Proposed Classification of Biopolymers

Biopolymer Classification	Bio-degradable	Non Bio-degradable
Extracted from Biomass	Starch, Cellulose (Bio-Naturals)	Polyamides e.g. Nylon (Bio-Synthetics ND)
Synthesised from Biomass	PHA, PHB, PLA (Bio-Synthetics)	Bio-PE, PET, PVC (Bio-Conventionals)

This classification enables the biopolymers compatibility with existing conventional polymer waste types to be identified. The remainder of this section considers the main polymers that fall within each of these four groups.

Bio-Naturals (Renewable, Extracted and Degradable)

Starches: These were one of the first of the new biopolymer developed to directly replace a conventional polymer packaging application. Starch 'peanuts' for loose foam fill, was one of the first applications when it was introduced in the 1990's, and at the time accounted for approximately 80 per cent of the overall bioplastics packaging market. Today thermo-plastic starch is still an important and widely used bio-plastic, particularly when mixed with or laminated to other polymers.

In order for starch to be processed thermo-plastically, sorbitol and glycerine are usually added. To improve resistance to water and bio-degradation, conventional polymers such as polyester, polyesteramids, polyesterurethanes or polyvinylalcohols can be added. Using different quantities of additives allows the TPS to be tailored to meet the specific needs of the packaging process or application, utilising existing production equipment to produce carry bags, yogurt tubs, drinking cups, plant pots, cutlery, diaper foil, coated paper and cardboard (Bakker, 1986).

Cellulose: Cellulose is produced mainly from wood and its introduction as a 'moisture proofed' coated cellophane film by DuPont in the 1920's revolutionised the food packaging industry. Cellophane's rise continued until the introduction of the first oil derived plastics films in the late 1940's after which it rapidly lost market share.

Today cellulose is returning to the packaging markets, often combined with other polymers, aided by the advances in cellulose blending and coating technologies. In particular there has been an increase in the use of cellulose with paper or board, as it does not inhibit their recycling. In addition to the potential environmental benefits, these combinations offer other advantages such as heat resistance and good thermal insulation properties (Bakker, 1986).

Bio-Synthetics (Renewable, Synthesised, Biodegradable)

Polylactic Acid: This began development in the mid 1990's, although it was a joint venture between the companies Cargill and Dow that created the first commercial manufacturing plant under the trading name of Natureworks, who began to produce PLA in sufficient quantities and of consistent quality to allow its use as packaging for mainstream consumer products (NatureWorks LLC, 2013d).

One of the more notable applications of PLA was in bottles for mineral water and fruit juices, which began in the early 2000's. PLA is visibly similar to the conventional plastic PET and can be processed on existing equipment with just minor modifications. PLA plastic is particularly suited for short-life packaging applications such as drinks containers, yoghurt cups, fruit, vegetable and meat packaging containers.

In pharmaceutical and medical spheres, PLA and its copolymers have already been used successfully for quite some time in the production of screws, nails, plates and implants that can be slowly absorbed by the body, therefore not requiring a second operation to remove them. In addition, suture material and agent depots made of absorbable PLA are also common bioplastics products.

PLA can be designed to biodegrade quickly or last for years, depending on the composition and quality, however it also has its disadvantages. PLA softens at temperatures of around 60°C, which limits its suitability for the production of cups for hot drinks. Yet copolymerisation with heat resistant polymers and the addition of fillers can result in greater heat stability. The world's first large PLA production plant was put into operation in 2002 in the United States with an annual capacity of 140,000 tons (NatureWorks LLC, 2011).

Polyhydroxyalkanoates: This material is currently less widely used than PLA. It also has potential packaging applications but has taken longer to commercialise due to the initial difficulties in achieving consist product quality. So far the most noticeable application has been as an injection moulding polymer to produce cosmetics packaging – compacts and lipstick.

Technically this material offers some benefits over PLA and Starch but is much less mature in its development. One of the key producers of PHA is Mirel with its first commercial plant in the USA due to be completed by late 2009 (Metabolix, 2013).

One of the key PHA's is **Poly-3-hydroxybutyrate,** whose molecular structure is shown in figure 3-11, and has similar properties to polypropylene but, with a glass transition temperature of 4°C, is brittle at low temperatures.

PHB has been used for the manufacture of injection moulded cosmetic packs and has also been processed into transparent film with a melting point higher than 130 °C, whilst remaining biodegradable after disposal.

The applications for PHB when blended with other materials range from the production of glues to hard rubbers. Cellulose acetate is often used as a blending material for certain packaging applications, where it can significantly reduce the overall cost (Bachtle, 2009).

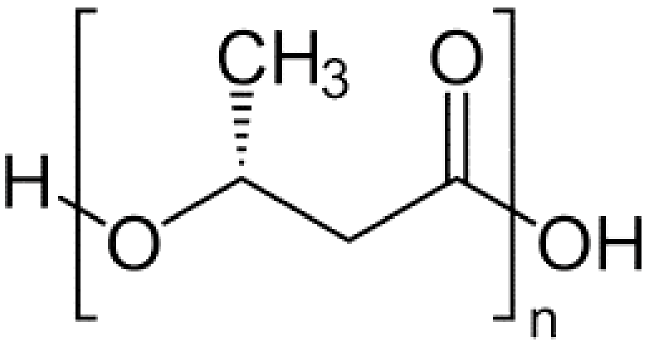


Figure 3-11: The molecular structure of 3-hydroxybutyrate, (Bachtle, 2009).

Bio-Synthetics (Renewable, Synthesised, Biodegradable)

Nylons are widely used in the packaging industry and whilst many types are produced from fossil fuels, one of the first nylons to be manufactured, Nylon 11 by the German company IG Farben in the 1940's, was actually derived from castor oil back (Smock, 2009). The initial success of this material, marketed as Rilsan 11, was primarily due to its unique properties rather than its renewability. Widely used in engineering, particularly in tubing for fuel and fluid transmission, Nylon also has packaging applications, often being used as one of the key barrier layers in a multi-layer high barrier flexible film (Arkema, 2005).

Today, other Nylons being produced from renewable resources include DuPont's Zytel® RS range which is largely based on the nylons PA1010 and PA610 that contain between 63% and 100% renewable content (sebacic acid) derived from castor oil (DuPont, 2012).

Bio-Conventionals (Renewable, synthesised, non-biodegradable)

Bio-PE, PP, PET and PVC (Bioethanol): As well as the development of new bio-polymers, such as PLA, PHA and TPS, with their own distinctive material and performance properties, conventional polymers such as polyethylene, polypropylene and polyester have also been produced from bioethanol-based ethylene manufactured from sugarcane and other crops. For some countries, such as Brazil, this is considered a viable alternative to oil derived plastics and it is claimed that these have a very low carbon footprint. These biopolymers have benefited from the investment in bio-fuels and can be used to replace all or part of the fossil derived polymer content as the two polymer types are fully compatible.

One of the first global brands to use this polymer in a mainstream product was the Coca-Cola company in its 'Plant Bottle', launched in 2009/10, (Coca-Cola Company, 2013). The PET used to make this bottle is manufactured from bio-PE and other fossil derived chemicals which limits the bio-derived component to a maximum of 30%. This of course does not account for the fossil derived energy used in manufacture, transport and processing. The main advantage of bio-conventional polymers is the compatibility with existing conventional polymers. This allows recycled PET to be used in the 'plant bottle' to further improve its environmental footprint (Coca-Cola Company, 2013).

3.3.3 *Polymer Properties and Packaging Applications*

The majority of polymers used for packaging are thermoplastics manufactured from non-renewable resources, such as crude oil and natural gas. Bio-polymers only account for around 1% of annual polymer production; however the majority of these are currently used in packaging and other short life, disposable applications. The following section provides a simple overview of the properties and current packaging applications for the main conventional and biopolymers.

3.3.3.1 Conventional polymers

A summary of the main conventional polymers used for packaging are shown in Table 3-4. The packaging applications listed in the table are based on the polymers being derived from petrochemicals not renewable resources. The reason for this is that, whilst their properties will be identical, their applications may vary due to the different commercial considerations; Conventional biopolymers are more expensive and less readily available than their petrochemical counterparts.

Polyethylene is one of the most widely used polymers and accounts for nearly half of the plastics used commercially (see Figure 3-8). The differences between a high density PE and a low density PE are so great that they have completely different packaging applications. When the ethylene is polymerised the monomers link to form chains of repeating units of 50 to 50,000.

During this process some side branching of the polymer chain occurs, if these are few and short then as the polymer cools, the long parent chain will pack closer together forming a high density PE. If large amounts of branching occur then a low density PE is produced.

Linear low-density PE is created by increasing side branching through the introduction of monomers such as butane, hexane or octane. This increases the number of branches to lower the density but the branches are shorter so giving different properties such as increase puncture resistance and strength. The density of the PE produced can be controlled by altering the temperature, pressure and time, with the polymer density decreasing as these factors are increased.

Table 3-4: Main Conventional Thermoplastics used in Packaging Applications

Polymer Type	**Properties**	**Packaging Applications**
Low-Density Polyethylene (LDPE) and Linear Low-Density Polyethylene (LLDPE).	Semi-rigid, translucent, tough, weather-proof, good chemical resistance, low water absorption, easily processed by most methods, low cost.	Squeeze bottles, toys, carrier bags, high frequency insulation, chemical tank linings, heavy duty sacks and general packaging.
High-Density Polyethylene (HDPE)	Flexible, translucent / waxy, weatherproof, good low temperature toughness (to -60'C), easy to process by most methods, low cost, good chemical resistance.	Major applications in chemical drums, Jerri cans, bottles, carrier Bags, food wrapping films etc.
Polypropylene (PP)	Rigid, opaque, good dimensional stability at high temperature and humidity conditions, difficult to process (blended to ease injection moulding), tough.	Polypropylene is one of the most versatile polymers available, used both as a plastic and as a fibre, across a range of markets.
Polyvinyl Chloride (PVC)	Compatible with many different kinds of additives - PVC can be clear or coloured, rigid or flexible. Formulation is the key in pvc application.	Blood storage bags, packaging films, cling film, blisters and clamshells, trays etc.
Polyesters: Poly-ethylene-terephthalate (PET, APET, CPET)	PET has excellent processing characteristics, high strength, rigidity and good temperature stability.	Drinks bottles, food trays, films, ovenable and microwaveable packaging.
Polystyrene (PS)	Brittle, rigid, transparent, low shrinkage, low cost, excellent X-ray resistance, free from odour and taste, easy to process.	Toys and novelties, rigid packaging, refrigerator trays and boxes, cosmetic packs and CD cases.
Nylons / Polyamides (PA)	Nylons tend to be semi-crystalline and are generally tough materials with good thermal and chemical resistance. The properties of the different grades, such as specific gravity, melting point and moisture content, tend to reduce as the nylon number increases.	Nylon films is used widely for food packaging, offering toughness and low gas permeability, coupled with heat resistance, for boil-in-the-bag packaging.

3.3.3.2 Biopolymers

Thermoplastic starch was one of the first bio-polymers used commercially as an alternative to a conventional polymer for a packaging application. The expanded TPS ‘peanuts’ were developed and used as a direct replacement for Expanded Polystyrene (EPS) chips used as loose fill for distribution packaging. A key benefit of this material was its readiness to degrade if allowed to escape into the environment; starch readily dissolves in water. A negative was its potential as a food source for vermin, which caused issues in warehouses until alternative formulations could be developed. Other uses that employ its water solubility properties include its use in drug capsules in the pharmaceutical sector, which provides an easy to swallow, tasteless mechanism for ingested drug delivery.

TPS accounts for around 50% of the bioplastics market although some sources state this to be higher. TPS can be processed using a range of technologies, into a variety of packaging materials such as through extrusion into films and sheets, or cast and moulded into rigid items. Examples of packaging made from TPS includes: carrier bags, yoghurt tubs, drinking cups, plant pots, cutlery, diaper foil, coated paper and cardboard. (InnovativeIndustry.net, 2010).

Regenerated Cellulose is one of the earliest and most widely used commercially available biopolymers. RC is produced almost exclusively from (soft) wood, and its development as a packaging film by DuPont, with the introduction of a ‘moisture proofed’ coated cellophane film in the 1920’s, revolutionised the food packaging industry. With waxed paper as its main competitor, the use of cellophane grew rapidly such that by 1938 cellophane accounted for 25% of DuPont’s profits. Cellophane’s rise continued until the introduction of the first oil derived plastics films in the late 1940’s such as PP and PE, these offered superior performance properties and cost benefits compared to cellophane which rapidly lost market share (DuPont, 2013).

However since the growing consumer concerns over packaging waste causing environmental damage and the realisation that the current use of fossil fuels is not sustainable, cellulose has found a niche as an ‘environmentally friendly’ packaging material. Today, examples of packaging made from cellulose, aided by the advances in cellulose blending, lamination and coating technologies, can be found in a range of consumer goods markets including food and cosmetics. In particular, cellulose has been used in combination with paper and board for food trays; as the cellulose material, unlike conventional polymers, can be easily removed during the paper recycling process. In addition to the environmental benefits, these new applications offer other advantages such as oven use and better thermal / insulating properties.

Polylacticacid was discovered in the mid 1990’s, but it was a joint venture between Cargill and Dow that created the first commercial manufacturing plant under the trading name of ‘Natureworks’ which began to produce PLA in sufficient quantities and of consistent quality to allow its use in mainstream consumer products. The most visible of these has been in bottles for mineral water and juice which began to appear in the marketplace in the early 2000’s (Natureworks LLC, 2013b). PLA plastics are especially suited for short-life, disposable packaging films and formed items such as drinking or yoghurt cups, fruit, vegetable and meat bags and wraps. In pharmaceutical and medical spheres, PLA and PLA copolymer plastics have been used for the production of suture threads, screws, nails, plates and implants that will overtime be absorbed by the body.

PLA is a transparent plastic made from natural resources. It not only resembles conventional petrochemical mass plastics (like PE or PP) in its characteristics, but it can also be processed easily on standard equipment that already exists for the production of conventional plastics making it a very versatile bio-plastic. It can be designed to biodegrade quickly or last for years, depending on the composition and quality. Additionally, PLA possesses good stability, as well as an extremely high transparency. However PLA also has potential disadvantages; the plastic softens at a temperatures above 60°C, which limits its suitability for the production of cups for hot drinks, although copolymerisation with heat resistant polymers and the addition of fillers can result in greater heat stability (Natureworks LLC, 2013c).

PLA that is produced from glucose is deemed to be extremely cost-efficient and is therefore even more viable as an alternative to mass plastics. The world’s first large PLA production plant was put into operation in 2002 in the United States with an annual capacity of 140,000 tons (NatureWorks LLC, 2013d).

Polyhydroxyalkanoates are not as commercially advanced as PLA and TPS, but have some notable packaging applications. One of its first uses in packaging was as an injection moulding polymer to produce cosmetics packs – compacts and lipstick.

Technically this material offers some benefits over PLA and TPS but is much less mature in its development. Poly-3-hydroxybutyrate, a type of PHA, has characteristics similar to those of the petrochemical-produced plastic polypropylene. One of the key producers of PHAs and PHB in particular is Mirel. Its first commercial plant in the USA due to be completed by late 2009 and with other companies aiming to begin production or to expand their current production capacity, it is likely that prices will fall to around 5 Euros per kilogram which will make the use of PHA more commercially attractive .

PHB is distinguished primarily by its physical characteristics. It produces transparent film at a melting point higher than 130°C, and is biodegradable without residue. Combined with other substances, PHB is also offered as a PHB blend. The application of PHB blends ranges from the production of glues to hard rubber. Characteristics that are specifically required in the blends can be developed by adding cellulose acetates, which can lower the production cost. Cork, starch or inorganic substances could also be added in order to meet special requirements of end products (European Bioplastics, 2013).

Conventional biopolymers such as bio-PE, bio-PP and bio-PET, have been synthesised from bio-ethanol produced from agricultural crops such as sugarcane. For some countries, such as Brazil, this is considered a viable environmental alternative to oil derived plastics and it is claimed that these plastics have a lower carbon footprint than their conventional counterparts. These biopolymers have benefited commercially from the investment in bio-fuels and can either be used to partially or fully replace the existing oil derived polymers within a pack without modification in production or contamination of the recycling chain. Coca-Cola, a leading soft drinks manufacturer, uses bio- PET mixed with recycled PET in its ‘Plant Bottle’ that was launched to market in Europe during 2009/10 (Coca-Cola Company, 2013).

3.4 Plastic Packaging Formats and Manufacturing Methods

In the previous section the common polymers used to make plastic packaging were identified and the key packaging applications of each polymer type were highlighted. In practise however, particularly in the food, pharmaceutical and drinks industries, plastic packs are often made from a combination of polymers, each with their own properties, to provide a pack that is tailored to the specific needs of the product contained.

However the majority of plastic packages can generally be classified into one of three categories based on a simple physical material/pack characteristics: Flexible, Semi-rigid and Rigid (Table 3-5). The processing of thermoplastics into these different packaging types will usually involve either a form of extrusion or moulding. Extrusion is usually a continuous process and normally requires an additional process (conversion) to make the final pack. Moulding on the other hand is usually an intermittent process and generally produces the final packaging item which can then be filled and sealed.

A more detailed description of the manufacturing methods for different pack and material types can be found in 'The Wiley Encyclopaedia of Packaging Technology' (Bakker, 1986) and the 'Fundamentals of Packaging Technology' (Soroka, 2002). The following section provides a brief and simplified overview of some of the main production processes used to manufacture plastic packaging, as outlined in Table 3-5.

3.4.1 *Flexible Plastic Packaging*

Flexible plastic packaging is one of the most technically advanced groups of packaging in use today, and provides an excellent performance to weight ratio. The manufacture of a flexible package will usually involve a number of stages following the production of the polymer resin. The first is the extrusion of the film either as flat sheet or tubing, from resin using a casting or blowing process.

Table 3-5: Pack processing methods

Packaging and Process Types	Extrusion	Extrusion / Moulding	Moulding
Flexible	Blown Film Cast Film Co-Ex Lamination		
Semi-Rigid	Sheet	Thermoforming: Vacuum / Pressure	
Rigid	Profiles, such as PVC window frames.	Extrusion Moulding	Injection Blow Moulding Injection Moulding Expanded Foam Moulding Rotational Moulding

The second is the processing of the film or tubing to the customers' requirements such as slitting and reeling, lamination, printing and coating. The third stage is the shaping and forming of the film or tube into the pack, which can be pre-made, produced in-line as a separate process, or produced as part of the product packing process, i.e. the material is formed around a product and sealed in one operation. The following production methods described are considered common to both conventional plastics and bio-polymer plastics unless otherwise stated.

3.4.1.1 Extrusion - Blown Films

In the production of blown films, the molten plastic resin is forced vertically (extruded) through a circular die, forming a continuous tube of plastic, which is simultaneously inflated with air to form a bubble (Figure 3-12). The bubble size is controlled by: the extrusion rate, material draw of, and air pressure. As the tubing is drawn of it is cooled and passes through a number of rollers before being reeled. Depending upon whether the material is required as flat sheet or tubing, prior to winding it can be slit and trimmed (British Plastics Federation, 2013). The main types of polymers used by this method to produce films are polyethylene, mainly low and liner low (LDPE and LLDPE) and PVC.

Other materials can often be included as blends with these polymers as blends or as individual layers in a co-extruded multi-layer structure such as PP, PA and EVOH. Bio-polymers that can be converted using this method include: Bio-PE, PLA, PHA, PHB and some TPS blends.

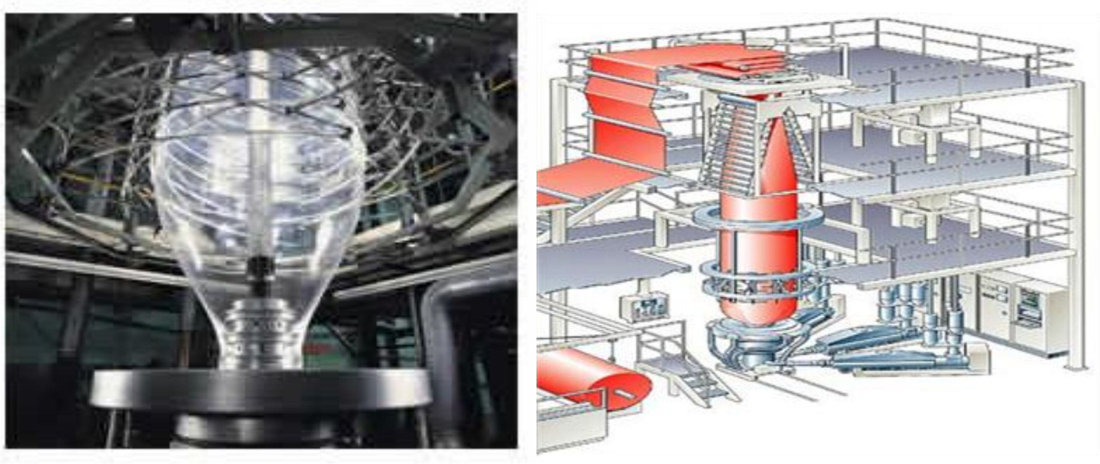


Figure 3-12: The Extrusion Blown Film Process (Source: British Plastics Federation)

The typical packaging products produced include plain bulk films such as shrink film, stretch film, bag film or container liners used mainly in secondary and tertiary applications such as transit or collation of products or in agricultural such as greenhouse film, crop forcing film and silage film. Higher value applications include films for consumer packaging such as lidding of trays, bags, and form, fill, seal (FFS), often the film will be printed. The types of packaging produced indirectly, requiring additional stages of processing, include laminated films, barrier film, and films for the packaging of medical products.

Applications for Biopolymer film produced by this process, in addition to those mentioned above, includes the agricultural application of crop forcing film. Here the biodegradability negates the need for the removal of the film from the crop after use, thus avoiding potential crop damage and the additional cost of removal and disposal.

3.4.1.2 Extrusion – Cast Films

For the production of cast films, molten resin is extruded through a flat die, which then passed through rollers that cool and polish the film. The material can be orientated in a particular direction, usually the machine direction, by stretching. Bi-axially orientated films however are stretched in both directions. Cast film has a number of advantages over blown film; the thickness tolerance can be better controlled making it more suitable for high speed printing processes, also the film is clearer as conduction cooling is faster than the convection cooling allowing fewer crystals to form. Through controlling the orientation of the film, it can be made to tear easily in one direction but not in another, a feature that can be exploited for ease of pack opening (PAFA, 2011).

3.4.1.3 Co-extrusion, Ex-Coating and Ex-Lamination

In **Co-extrusion** more than one polymer is delivered to the die head using a number of screw extruders. By controlling the size of the die and each extruder screw, the thickness of each polymer layer can be controlled. This is different to a polymer blend, as the polymers remain as separate layers. This is advantageous in that different polymers can be combined in one operation, whilst ensuring that properties such as sealing temperature, barrier, stiffness etc. can be optimised to a particular layer e.g. the inner layer for sealing.

In **Extrusion Coating** the molten polymer is extruded directly onto a substrate such as paper or foil, which is then passed between rollers to apply pressure for adhesion and to cool the polymer. This is often used to create a heat sealable inner layer for later pack production and sealing. In **Extrusion Lamination** the molten polymer is extruded between two materials such as paper and foil and the polymer acts as the adhesive. Applications for materials produced via these two extrusion processes would include carton drinks packages (British Plastics Federation, 2013).

Biopolymers are often combined with other materials using these extrusion processes to provide the necessary barrier properties. Depending upon the production volumes, films can be produced separately and lamination can be achieved as a second step. This is particularly applicable to printed packaging where the printed surface is contained within the lamination. Lamination in these cases is achieved with adhesives which can also provide barrier properties e.g. Ethylene Vinyl Alcohol (EVOH).

3.4.1.4 Forming and Finishing

Once a plastic film has been made it can be converted into a range of useful packaging products. These can be as simple as a plain film for wrapping, a printed film for bags or a complex laminated pouch. Whilst the processes will vary according to the material and type of flexible pack being produced, primarily they all involve the forming and sealing. Forming can be integrated with the filling process or take place prior to filling as in a pre-made bag. Sealing will be required to create the pack and then to close the pack once filled. If a bag is made from a single film, this will usually be folded in the machine direction and then sealed (using heat) and cut at given widths to create a bag (PAFA, 2011).

3.4.2 *Semi-Rigid Packaging*

Semi-rigid packaging process begins with the **extrusion of a thick film or sheet**. The thickness of the film or sheet will depend upon the application’s required draw depth and stiffness. For most packaging applications the thickness of the extrusion is sufficiently thin to allow it to be reeled, in which case its production is similar to flexible film extrusion. For thicker extrusions, reeling is not possible so the extrusion is cut into sheets. These are often used to make large formings such as pond profiles, body panels etc. The second stage of flexible packaging process involves the forming of the film or sheet. Certain specialist converters extrude and form the sheet in-line. This has an advantage in that when a pack is formed directly from the extruded sheet before it has cooled, it takes that shape more permanently and if reheated at a later stage, i.e.

during cooking, even if softened it will remain structurally stable. Packs formed from a cooled sheet that is reheated have a memory of the flat form and will try to return to this initial state when heated (this is the principle behind shrink films which are stretched in their softened but not molten stated). There are two key processes used for creating semi-rigid packs: thermoforming and vacuum forming.

3.4.2.1 Thermoforming

This is the process of forming a thermoplastic sheet or film into a three dimensional shape using heat and either pressure or vacuum or both. Figure 3-13 illustrates the key stages in the vacuum thermoforming process. Firstly the plastic sheet is heated, then a vacuum is used to draw the softened plastic into the mould, finally the moulding is cooled and ejected from the mould (Sinotech, 2013). An alternative method is to use a male mould where the film is formed over the tool rather than into it to give the shape required as shown in Figure 3-14, which also shows the use of air pressure to aid the forming process. Others processes use a mechanical plug to assist in the initial forming of the plastic. All these forming process can be used offline to produce packaging for later use, however in-line forming tends towards the negative tool as it allows product to be placed directly into the pack (tray, blister etc.) before closing and sealing.

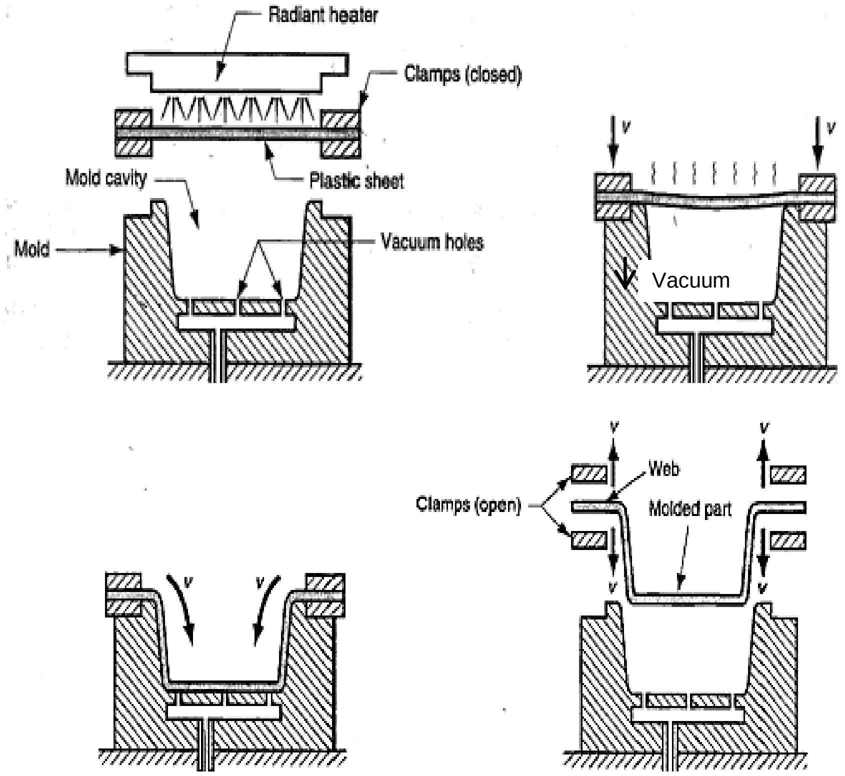


Figure 3-13: Stages in the Vacuum Thermoforming Process. Source: (Sinotech 2013)

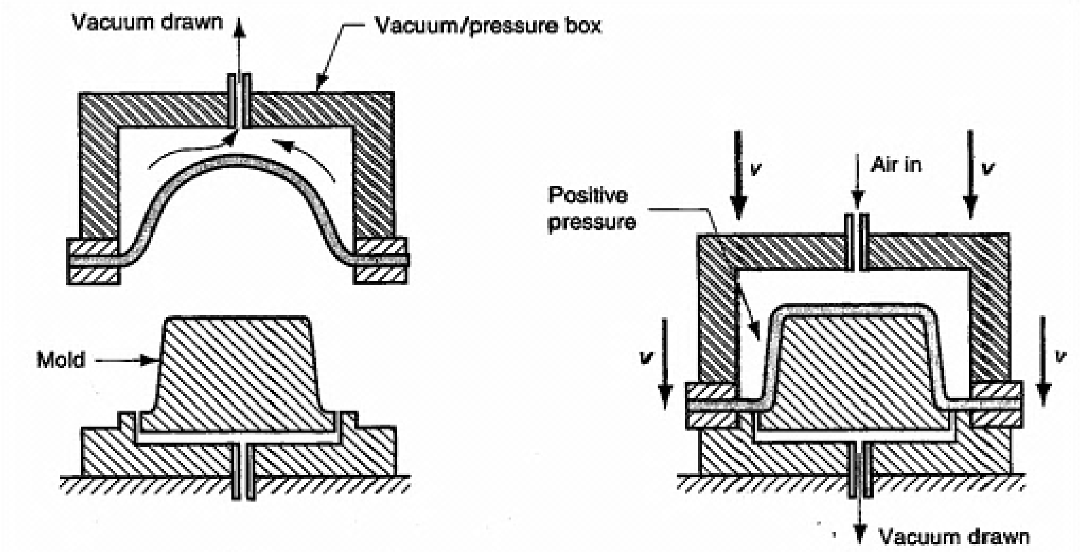


Figure 3-14: Vacuum Forming using a male or Positive tool. Source: (Sinotech 2013).

The types of packs produced by these methods include trays, clam shells and blister packs. The main limitation of thermoforming is usually the draw depth. The deeper the draw the thinner the material is stretched and thus the weaker it will be. As well as compression strength, the thickness of the material in the wall will also affect its other properties such as barrier to gases and water and puncture resistance. Selecting the right type of tool and forming method for the design of pack and ensuring the design facilitates the flow of material during forming can all be used to minimise the thickness of material required to meet the desired final pack performance.

In addition the equipment and pack cost of thermoforming, relative to other moulding processes, is quite cheap and flexible in scale and complexity. The process is also ideally suited to in-line operation with a packing/filling process; a tray can be formed, filled with product, then lidded and sealed, all automatically. This saves space and handling of raw materials as the cube of a reel of film is far less than the cube of the packs formed from it.

3.4.3 *Rigid Packaging*

Rigid plastic packs are formed primarily through a single moulding process, within a closed die usually under pressure, from a molten plastic or in a two stage process from a heated pre-form. Both these processes tend to be intermittent, however multiple items can be produced per cycle if a multi-cavity tool is used. Most thermoplastics are suitable for this type of moulding and include: Polyethylene, Polyethylene Terephthalate, Polyvinyl Chloride, and Polypropalene, as well as bio-polymers: Polylactic Acid, Polyhydroxyl Alkanoates, and Polyhydroxyl Butanoates. The remainder of this section considers the key moulding technologies used for rigid packaging manufacture.

3.4.3.1 Injection Moulding

One of the key strengths of injection moulding is the possibility to produce complex and intricate shapes as well as items with large depth to cross section ratios such as bottles. One of its limitations however is cost; the moulds used to make the parts can be very expensive and therefore only economical for large production quantities. A typical injection moulding machine, as shown in Figure 3-15, consists of two parts; an injection unit and a clamping unit.

The injection unit uses a simple two plate mould, as illustrated in Figure 3-16, and the process starts with plastic pellets from a hopper being fed into the injection unit, which in turn feeds a reciprocating screw. This mixes and heats the polymer and acts as a ram, injecting the molten polymer into the mould, after which it returns to its original position ready for the next moulding cycle. The second stage involves the clamping unit which operates the mould. It does this by keeping the two parts of the mould in alignment and holding them together during the injection of the molten plastic. After each injection cycle the clamping unit opens and then closes allowing the moulded parts to be released thus clearing the tool ready for the next cycle.

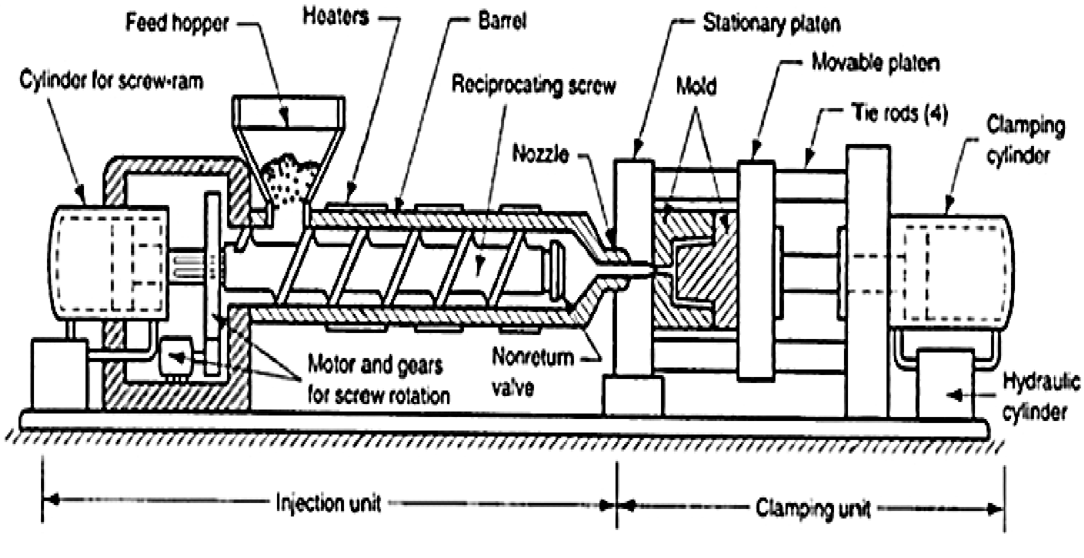


Figure 3-15: A typical reciprocating screw injection moulding machine. Source: (Sinotech 2013)

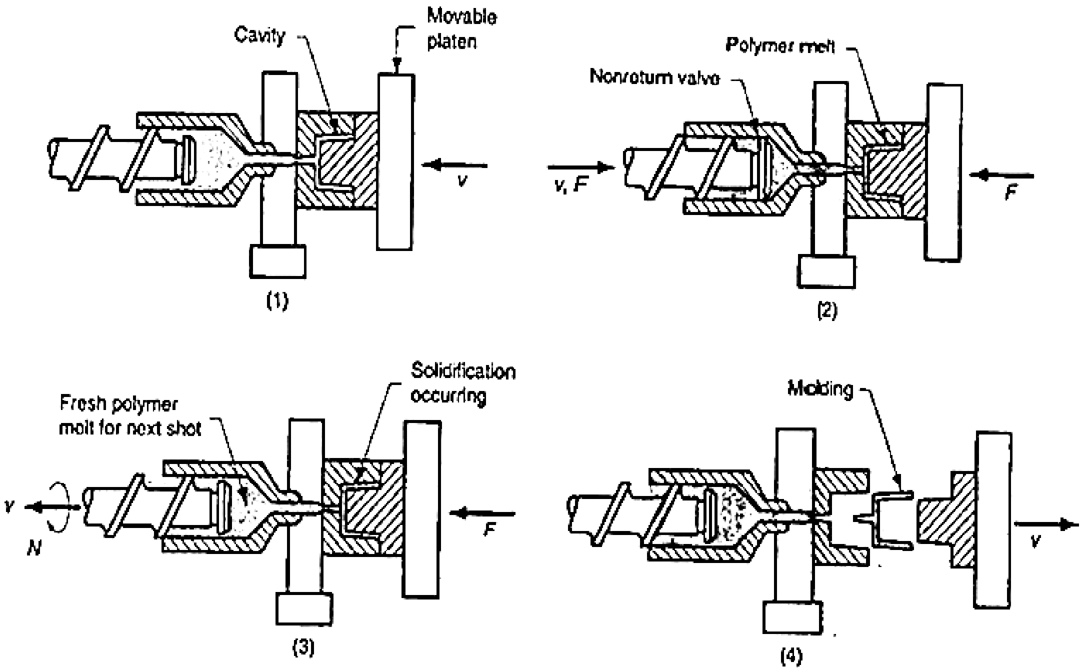


Figure 3-16: Injection moulding using a reciprocating screw. Source: (Sinotech 2013b)

More complex moulding can be produced using a three plate mould, whilst other features such as a cooling system can be incorporated to reduce cycle times and hot-runner moulds used to reduce polymer loss from the injection channels. Another, less common injection moulding system, uses a plunger to inject the polymer into the die. In this two stage machine, called a screw-preplasticiser, a screw extruder melts and mixes the polymer in one barrel, whilst the plunger inject the molten polymer in a second barrel. A single barrel plunger also exists which melts the polymer in the plunger barrel. For small, low pressure forming standard hydraulic clamps are adequate but for large forming requiring pressures exceeding 1000 tonnes, hydro-mechanical clamps are normally required (Sinotech, 2013b).

3.4.3.2 Blow Moulding

Blow moulding is used to make hollow seamless items that can range from small bottles to large drums, although it is generally used for high volume production of smaller disposable containers such as bottles for milk. Blow moulding is only suitable for thermoplastic polymers as heat is used to melt the polymer prior to forming. There are three main types of blow moulding used for making packaging: Extrusion, Injection and Stretch. In each case the basic principle of blowing air into a molten tube or parison of plastic which expands within the mould to form a hollow vessel open at one end.

In **extrusion blow moulding**, molten plastic is extruded, usually downwards, as a hollow tube or parison, which hangs unsupported from the extruder die head. The two halves of the mould then close over the parison, and air or nitrogen is forced in. The molten parison expands it to fill the mould and when sufficiently cooled the mould separates releasing the forming. This method produces some waste plastic or flash, which must be trimmed from the bottle and recycled (Figure 3-17). There are a number of variants of this process such as continuous or intermittent extrusion and single or multiple moulds depending on the polymer used, forming size, volumes and production speeds required. One of the limitations of extrusion blow moulding is that the wall thickness of the tube/parison is uniform and thus cannot be profiled to allow thicker walls on the sections that will be stretched most (Sinotech, 2013c).

Injection blow moulding is a high speed/volume process used to manufacture a range of hollow packaging products such as plastic bottles. It involves three stages: injection, blowing and ejection. The molten polymer is injected into a heated preform mould at high pressure, which is clamped around a mandrel forming the internal shape of the preform, as shown in part 1 of Figure 3-18. At this stage the preform consists of a fully formed neck with a thick tube of polymer attached. A cold blow mould is then clamped around the preform and air is blown in to inflate it to the shape of the mould.

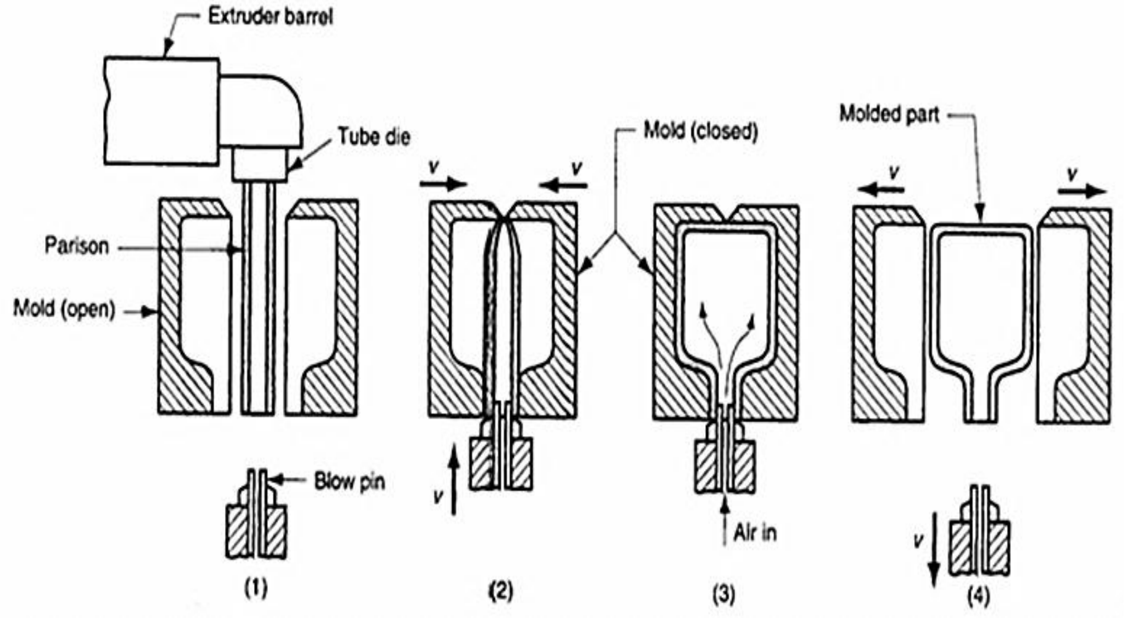


Figure 3-17: Extrusion blow moulding process. (Source: Sinotech)

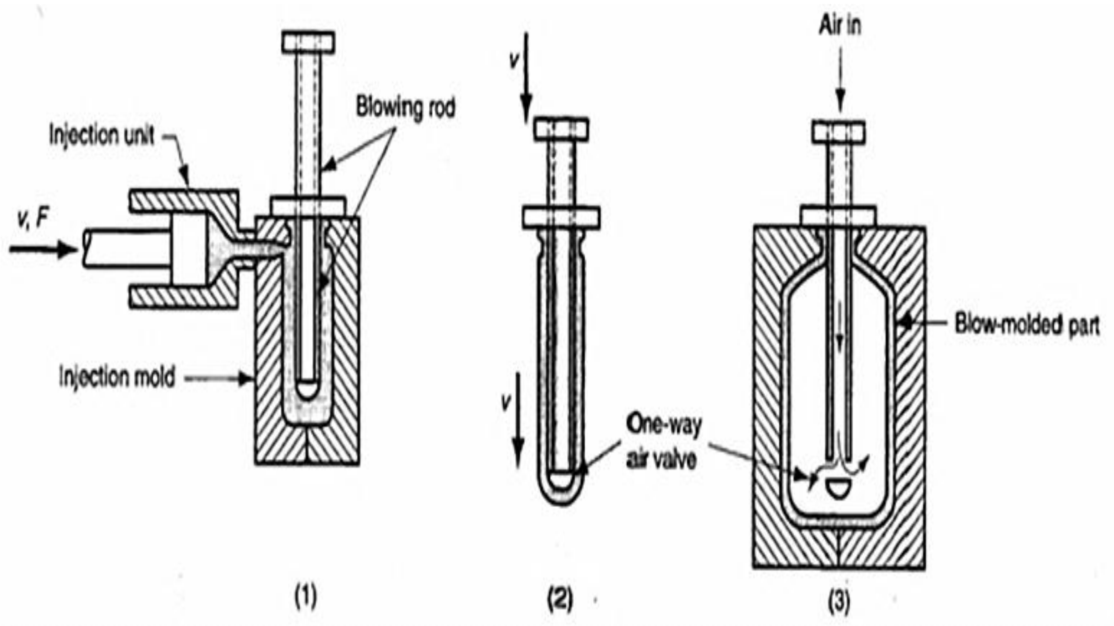


Figure 3-18: Stretch blow moulding process. Source: (Sinotech 2013b).

Once sufficiently cooled it is ejected and the process repeats. The injection blow moulding process allows greater control of the flow and distribution of material within the mould and more intricate detailing to be achieved, usually resulting in the bottle having a superior appearance and quality than an extrusion blow moulded bottle.

Stretch blow moulding is similar to injection blow moulding in that the plastic is first made into preforms using an injection moulding process and in a single machine process are then blown into the bottle shape. However in a two machine process the preforms are cooled and ejected and will be the input into the stretch blow moulding machine, which heats the preform before it is stretched and blown. The stretching is achieved with a core rod before blowing and with certain polymers, such as PET, results in strain hardening which allows the ‘bottles’ to resist deforming under the pressure of their carbonated contents (Sinotech, 2013c).

3.5 Chapter Summary

It is clear that plastics packaging plays a key role in our modern society and is an essential requirement of our highly sophisticated product supply chains. The demand for plastics packaging and plastics in general, is likely to increase as populations rise, consumption grows and the trend towards urbanisation continues. Furthermore, it has been demonstrated that plastics packaging can actually help preserve resources, reducing the loss of products through spoilage, wastage and damage. However, the need to reduce our dependence on fossil fuels due to their negative environmental impacts and declining availability, has seen a trend towards more sustainable materials, including the use of biopolymers for packaging. With UK government's commitment to an 80% reduction in carbon emissions by 2050, there will be increasing pressure on manufacturers to reduce their carbon footprints. However the apparent familiarity of bioplastics based on their visual similarity to conventional polymers can be misleading as they often differ substantially in their technical properties, processing, performance and EoL management.

Chapter 4 Review of Sustainable Packaging Design Methods, Processes and Software Tools.

4.1 Introduction

The growing acceptance of the need for greater sustainability, has led to a proliferation of new methods and tools targeted at companies to help them manufacture more sustainably. This particularly applies to their use of packaging which has often viewed by businesses as a cost rather than a benefit; a view extends through the supply chain where packaging is often perceived as an unwanted waste, rather than a necessary part of the product purchase. This resulted in packaging being an early focus for environmental legislation requiring companies to be accountable for the packaging they use. Numerous guides, methods and tools were initially developed to support companies in improving the environmental footprint of their packaging, which later developed to encompass all three pillars of sustainability. This chapter begins with an introduction to the packaging design methods and processes in use commercially for the design and development of consumer goods packaging, followed by a review of common, commercially available eco-design methods and tools used to support the sustainable design of packaging.

4.2 The Packaging Design and Development Process

"We can't solve problems by using the same kind of thinking we used when we created them." (Albert Einstein)

The process of developing or designing a new pack will vary in complexity according to the type of pack being developed, the product being packaged, the functionality required, the degree of automation and the scale of the business etc. In addition the organizational structure of the company can also add layers of further complexity with different aspects of packaging design and functionality being controlled at various levels within a business, from local semi-autonomous production units to a globally centralised head office. As shown in Figure 4-1 under business functions.

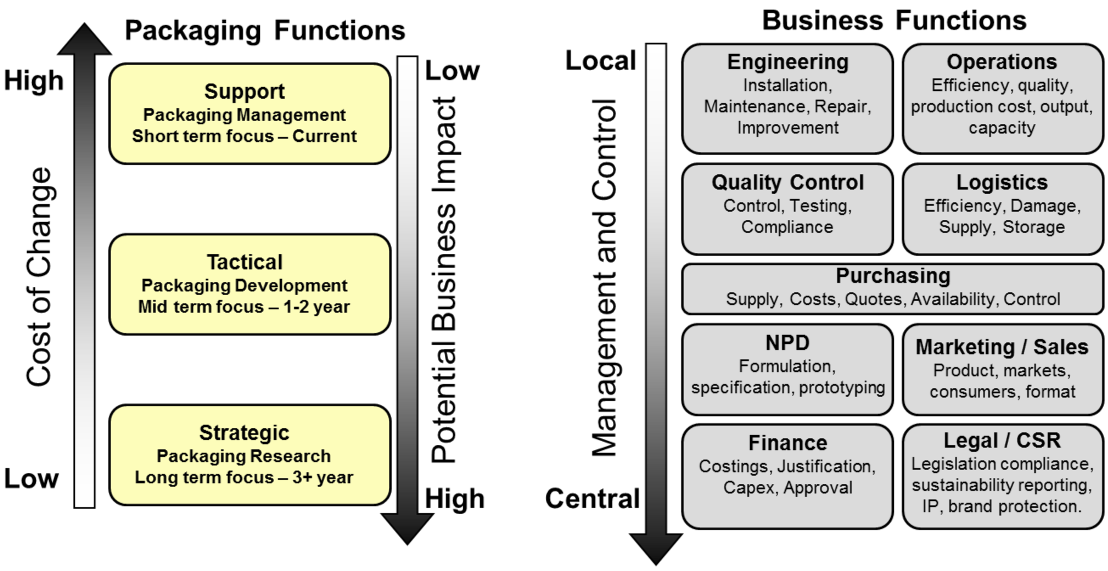


Figure 4-1: Organisational structure of typical packaging and business functions. Adapted from (Colwill, *et al.*, 2011)

Furthermore, even within simple organisations, responsibilities for packaging will extend across departments requiring a degree of compromise where conflicting demands are encountered. In larger organisations, particularly where a competitive advantage can be gained through packaging innovation, the packaging functions will often be divided into three groups according to the level of development. An example of a typical structuring of these three groups and their functions are shown in Figure 4-1. The down arrows on the right of the packaging functions indicate the potential impact that these groups can have on the business and whether the function is likely to be locally based or centralised, whilst the arrow on the left shows the increasing cost to the business to make a design change as it get closer to market.

The grouping of packaging functions as described has the benefit of enabling specific packaging functions to be aligned more closely to the most relevant business function. A key drawback however is that the communication and co-operation between the groups needs to be purposely maintained to ensure the skills and potential of the whole packaging function is optimised, particularly important for the successful development and implementation of new packaging. The horizontal and vertical connectivity required within an organisation and its supply chains is shown in Figure 4-2 with examples of how two business functions; purchasing and marketing, might interact vertically within the business on packaging related responsibilities.

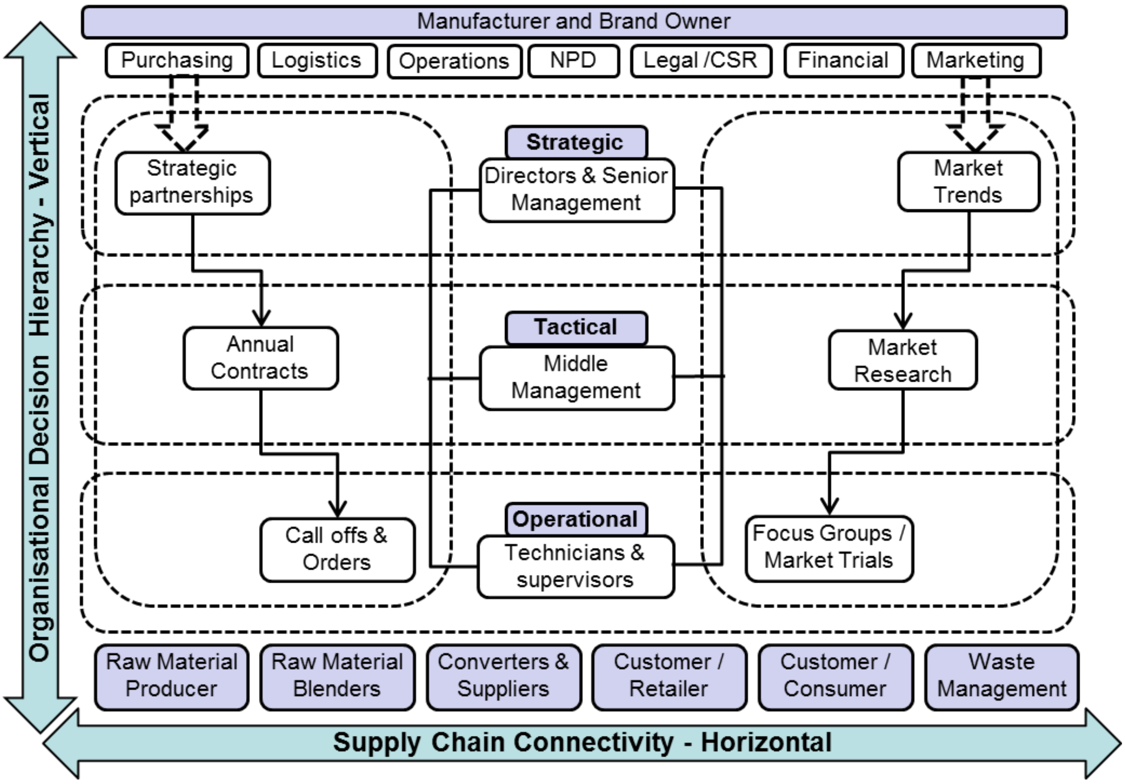


Figure 4-2: Vertical and Horizontal connectivity of packaging development functions. Adapted from (Colwill, ***et al.*****, 2012b).**

The process of designing and developing packaging within these types of organizations described is usually well developed and supported by internally and externally controlled methods, tools and processes. More recently the integration of sustainability considerations into the packaging design process has been advanced, and commercially available software tools and design guides have been developed to support this. The use of biopolymer packaging, whilst linked to sustainability, is more complex and potentially contentious due to the lack of consensus on its sustainability benefits and the lack of reliable data on their performance over their life cycle due to the novelty of the materials. Clearly the decision by a company to use biopolymer based packaging will ultimately require a variety of inputs from different personnel, departments and actors within the company and its supply chain, however the initiator of this process is likely to be a strategic one as the use of biopolymers will generally have high visibility within the marketplace, e.g. the CocaCola ‘Plant Bottle’ (Coca-Cola Company, 2013) and PepsiCo ‘Sunchips’ (Guzman, 2011), and be driven by a perception that the use of biopolymers will contribute towards achieving the company’s sustainability goals.

4.3 Packaging Eco-Design Tools, Methods and Guidelines.

There are a number of packaging eco-design tools, which are commercially available to packaging designers and developers to support their activities. Some of these are specific to packaging, whilst others are more general and have a broader range of eco-design applications. This review focuses primarily on software tools targeted specifically at supporting the sustainable packaging design process but includes other widely used eco-design tools, which have a much broader range of application. In addition, a review of published literature on eco-design tools was undertaken, including single and multiple tool reviews.

Whilst the primary objective of this review chapter is to identify and assess existing eco-design tools, methods and guidelines that can be used to support the sustainable packaging design process, it also identifies the current weaknesses and gaps in support offered by commercial products. In all, 40 tools, methods and guidelines were assessed using a combination of original tool assessment and previously published studies. This section begins with a review of previously published studies and then considers a selection of the key software packages available for sustainable pack design.

4.3.1 *Reviews of 'packaging' Eco-design Tools*

Reviews of eco-design tools, with a specific focus on packaging, are limited both in number and content. However reviews of eco-design tools that can be applied to packaging eco-design are wider ranging and provided a suitable foundation for review of packaging eco-design tools later in this chapter. Furthermore, the strengths and weaknesses of the different assessment criteria and categorisations used in these reviews were investigated and the results used to inform this latter review. In all 8 review papers were assessed and a short summary of each is now provided.

Five Winds International, 2008. (Report) (Five Winds International, 2008)
Inventory of sustainable packaging initiatives and proposed approach to develop sustainable packaging guidelines.
The aim of this study by Five Winds International (FWI) was to provide an inventory of existing sustainable packaging initiatives in order to identify guidelines, standards and tools that are both established and of merit to the aims and objectives of their client, the Canadian Council of Ministers for the Environment (CCME), defined as "to provide

guidance on the development and implementation of Extended Producer Responsibility (EPR) and product stewardship programs with packaging as a first priority”. It was therefore not the objective of the authors to evaluate the tools but merely to assess their potential for adoption by the client.

The review method involved desktop research and interviews with ‘knowledgeable’ individuals rather than assessment of each tool by the author, as such the impartiality of these ‘knowledgeable individuals’ and how the consistency of assessment was maintained is unclear. However, the set of criteria used to assess each initiative ‘tool’ was approved by the CCME and 15 stakeholders then reviewed the initial findings with their feedback being used to inform the final report. The ten criteria used included a classification of the approach used by the initiative ‘tool’ (Scorecard, Guidelines, Regulation, Tool, etc.), and its intended user (Consumers, designers, technologists etc.). Other criteria included its scope, metrics used, gaps, targets, barriers to adoption and usefulness. Finally each ‘initiative’ was rated in terms of its suitability for adoption (Adopt, Adopt with modifications, Consider some elements, not recommended).

Whilst the review did not provide a complete and thorough assessment of each initiative it identified certain attributes common to the ‘initiatives’ reviewed namely; the use of a life cycle approach and the inclusion of key performance indicators, and also highlighted requirements that were absent or not fully met by the initiatives, such as: lack of social performance parameters (excluding health and safety), lack of inclusivity for all actors within the supply chain (tools tended to be targeted at specialist users such as designers), lack of specific guidance (e.g. material selection, implementation), lack of holistic system view (product, use, etc.) and finally no formal feedback system to validate and measure actual benefits achieved.

In summary the study by FWI provided useful insights but was limited both in terms of scope and ambition, concerned mainly assessing the tool in terms of its possible adoption by the client. The 13 initiatives reviewed are listed in Table 4-1, with selected key attributes for each review included in separate columns. The final column, headed ‘Select’, identifies the tools which are considered to be relevant to this research, and thus have been selected for independent review by the author in section 4.4. These have been labelled ‘Yes’. The tools not selected were either not relevant, to broad or have been superseded by later software versions or tool adaptations.

Table 4-1: Summary of tools reviewed by Five Winds (Five Winds International, 2008)

Initiative reviewed	Type	Year	Life cycle Perspective	Performance indicators	Intended User	Select
Sustainable Packaging Coalition	Design Guidelines	2006	Full	11 general	Designers	Yes
Sustainable Packaging Coalition - MERGE	Tool v1 Tool v2	2001 2008	Partial (cradle-gate)	13 specific	Designers	Yes
WRAP's guide to evolving packaging design	Design Guidelines	2007	Full	5 general	Companies general	Yes
Wal-Mart packaging criteria/scorecard	Scorecard & DG's	2006-2008	Partial	8 specific 1 general	Suppliers	Yes
SC Johnson Greenlist packaging criteria	Scorecard & DG's	2001	Partial - no use phase.	8 general	Designers	Yes
Johnson & Johnson packaging design and selection; DfE tool	Design Guidelines		Partial - Mainly end-of-life	Various	Designers	Yes
European Commission	Regulation	1994	Partial	Specific	Companies	No
BASF Eco-efficiency analysis tool –	Tool v1	1996	Partial	6 general	Skilled engineers	No
BASF SEEbalance analysis tool	Tool v2	2006	Full	6 general	Skilled engineers	Yes
INPEN Packaging code of practice	Guidelines v2	2003	Full	7 general	Designers	Yes
INCPEN Packaging Watchdog	Watchdog Guidelines	2007	Partial	Unclear	Companies Consumers	No
Sustainable Packaging Alliance - PIQET	Tool	2007	Full	Various	Technologists	Yes
EPEAT- Electronic product environmental assessment tool	Tool	2007	Full	23 mandatory 28 optional	Not suitable for packaging	Yes
Climate Counts (Not packaging specific)	Scorecard	2007	Partial	22 general	Consumers	No

Liubkina-Yudovich E. 2010. (Thesis) (Liubkina-Yudovich, 2010)

Qualitative versus Quantitative data tools for sustainable packaging design at Eastman Kodak Co.

The two packaging eco-design tools reviewed were COMPASS (Quantitative based tool) and PDOT (a qualitative based tool). The purpose of the study was to compare the two approaches taken by the tools, Qualitative and Quantitative, and determine which performed best in a commercial situation (Packaging Design Dept. of Eastman Kodak). The study however was potentially floored as the PDOT tool had been developed by Eastman Kodak Engineers and therefore could be positively biased towards it. Also the study sample of participants was very small and not statistically meaningful. However, it did provide useful insights into the practical application of the tools and the difficulties in getting new methods adopted.

Novkov S., 2008. (Conference Paper) (Novkov, 2008)

Sustainability management of industrial enterprises advanced concepts, techniques and tools.

Whilst identifying approximately 70 concepts, techniques and tools and providing guidance on where they may provide benefit during the decision making process the study did not provide guidance on their usefulness for packaging eco-design or provide an assessment of the tools strengths and weakness. This study provides a comprehensive list of existing tools and was used to inform the later review, however there was insufficient information to enable this assessment to be made from the paper alone and additional investigation of each tool listed was required.

Byggeth S., and Hochschorner E., 2006. (Journal) (Byggeth & Hochschorner, 2006)

Handling trade-offs in Eco-design tools for sustainable product development and procurement.

Provides a clear and concise analysis of 15 eco-design tools currently in use. Although these tools were not developed specifically for packaging application, they could be applied to this purpose offering varying degrees of support. The tools were assessed largely on their ability to provide decision support during the eco-design process in trade-off situations particularly in the area of sustainability. The conclusion of the report was that none of these tools provided adequate decision support by themselves but could form part of a framework for sustainable design.

Huo L., Saito K., 2007. (Journal Paper) (Huo & Saito, 2007)

Concept identification and implementation of sustainable packaging systems.

The paper begins with the identification, definition and subsequent characterization of sustainable packaging systems and how they must perform. This is followed by a brief overview of 7 design and innovation tools that were developed to advance sustainable packaging. It noted a number of shortcomings with the tools identified the most important being that the current tools were not adequate and needed improving to be more integrated, holistic and user-friendly. Also it noted that tools should be more accessible to all stakeholders and improvement in multi-criteria decision making was needed. Finally it asserted that these sustainable-design tools should not only identify improvements but also offer solutions.

Lawrence et al., 2002. Corporate Social Responsibility and Environmental Management.

Applying organizational tools and techniques.

This paper summarised a two year case study in the automotive sector which investigated how existing quality management tools used for ISO9000 could be used for environmental management accreditation i.e. ISO 14001. In addition to identifying 38 existing tools and techniques that might lend themselves to environmental application, the study proposes how 18 of these might be used at different stages of the business process and by which organisational functions. Although it does not provide any detailed evaluation of any particular tool or technique, it does identify 'lack of factual information' as a limiting factor in implementing some environmental techniques.

Lewis et al., 2007. Sustainable Packaging Alliance. (Report) (Lewis, et al., 2007)

Sustainable Packaging Redefined

A report by the Australian based, Sustainable Packaging Alliance (SPA), it begins with a series of definitions and assertions as to what makes a package sustainable. The paper then reviews 3 initiatives and 5 packaging eco-design tools at a fairly basic level. In addition to proposing a more detailed set of Key Performance Indicators (KPI's) for measuring packaging sustainability, the paper also highlights a number of research gaps in this field that include best practise, biopolymer packaging, social impacts, environmental labelling.

Knight P. and Jenkins J.O., 2009. (Journal Paper) (Knight & Jenkins, 2009)

Adopting and applying eco-design techniques: a practitioner's perspective.

This study is primarily concerned with how a suite of existing eco-design tools can be customised to meet the needs of a particular product development process and identifies the most appropriate eco-design tools for this purpose. This serves to provide a review of different eco-design tools and offers a useful classification method for doing so.

Each of the reviews discussed in this section have been summarised in Table 4-2, which includes the key methods used in the review, the applicability to packaging design and whether they have any value in informing the review of packaging tools in section 4.4, indicated in the last column as either having no real value 'Little', some value 'Partial' or high value 'Yes'.

Table 4-2: Summary of previous reviews, methods used and value to future review.

Authors / Type	Title	Year Pub.	Tools Rev.	Tools Rated	Pack Focus	Method	Value
Five Winds International Report	Inventory of Sustainable Packaging Initiatives	2008	13	No	Yes	Qualitative Subjective Basic	Partial
Liubkina-Yudovich E. RIT, Thesis	Qualitative versus Quantitative data tools for sustainable packaging design at Eastman Kodak Co.	2010	2	Yes	Yes	Qualitative Subjective Detailed	Little
Novkov S. Conference Paper	Sustainability management of industrial enterprises advanced concepts, techniques and tools	2008	70	No	No	List Overview Application	Partial
Byggeth S., Hochschorner E., Journal Paper	Handling trade-offs in Ecodesign tools for sustainable product development and procurement.	2006	15	Yes	No	Analytical Detailed	Yes
Huo L., Saito K., Journal Paper	Concept identification and implementation of sustainable packaging systems	2007	6	No	Yes	Analytical	Yes
Lawrence *et al.*, Journal Paper	Applying organizational tools and techniques	2002	38	No	No	Practical	Partial
Lewis *et al.*, Report	Sustainable Packaging Redefined	2007	8	Basic	Yes	Qualitative Consultative	Partial
Knight and Jenkins Journal Paper	Adopting and applying eco-design techniques: a practitioners perspective	2009	15	Yes	No	Analytical Assessed	Partial
Totals			**167**				

4.4 Review of selected 'packaging' eco-design tools

From this review of published works in section 4.3, a further 15 additional tools were reviewed across a range of assessment criteria some with a slightly broader application than just packaging eco-design. In particular a number of specialist LCA tools were considered. LCA is mainly used in industry to assess the environmental impact of a product, component or pack, although it can also be used to assess and compare processes, such as riveting or welding. Depending on the complexity of the product or process being assessed, this will usually require considerable time and effort to compile an inventory of the resources used (inputs) and emissions created (outputs) and often involve the processing of large amounts of data.

A number of commercially available software tools are commercially available to facilitate this process, the majority of which follow the methodology prescribed in the internationally recognised standards for LCA (ISO14040 and ISO14044). The following review considers three of the most commonly used; SimaPro, GaBi, and the Cambridge Engineering Selector CES Eco Audit Tool. For a more extensive review of specific LCA software please refer to Jönbrink *et al.* (2000).

The results of this initial packaging eco-design review are provided in **Table 4-3**, which identifies the product reviewed, the type of product (Tool, Guide, Scorecard or Database), what stages of the life cycle were covered (Full, Partial, Cradle to Gate, End-of-Life), what types of performance indicators were used and how many, the typical intended user (e.g. Expert, Novice, Designer, Engineer), whether it is used for designing/developing packaging, does it provide specific information or advice on biopolymer materials and does it provide specific strategic support within the design process.

Table 4-3: Packaging design tool review and comparison results

Name of Product Reviewed	Type of product	Life Cycle Scope	Performance indicators	Intended User Type	Pack Design Use	Bio-Polymers	Strat Supp
BASF SEE balance analysis tool V2	Tool	Full	6 general	Technical	Partial	No	No
The CES Eco Selector	Tool	Full	Various	Engineers	Partial	Some	No
COMPASS	Tool		Various	Designers	Yes	No	No
EPEAT- Electronic product environmental assessment tool	Tool	Full	23 mandatory 28 optional	Engineers	No	No	No
GaBi v6	Tool	Full	Extensive	Experts	Final	Some	No
Greener Package	Database	Partial	None	General	Yes	No	No
INPEN Packaging code of practice	Design Guide v2	Full	7 general	Designers	Yes	No	No
DfE tool	Design Guide	Partial - EOL	Various	Designers	Yes	No	No
SC Johnson - Greenlist	Database and Design Guide	Partial - no use phase.	Single rating	Designers	Yes	No	No
SimaPro v7.3	Tool	Full	Extensive	Experts	Final	Some	No
Sustainable Packaging Alliance - PIQET	Tool	Full	Various	Technical	Yes	Yes	No
Sustainable Packaging Coalition	Design Guide	Full	11 general	Designers	Yes	Yes	No
Sustainable Packaging Coalition – MERGE v 2	Tool	Partial (cradle-gate)	13 specific	Designers	Yes	Yes	No
WRAP's guide to evolving packaging design	Design Guide	Partial	5 general	Companies general	Yes	Yes	No
Wal-Mart packaging criteria/scorecard v2	Scorecard / Design Guide	Partial	8 specific 1 general	Suppliers	Yes	Yes	No

As can be seen from the **Table 4-3** the majority of products take a life cycle approach and can be used for packaging design but require specialist skills to use and do not provide strategic support or detailed data on biopolymer performance. All the LCA based tools reviewed are able to model common pack types obtaining key material and process impact data from external databases such as Eco Invent, whilst the comprehensive LCA packages such as SimaPro (Pre Consultants, 2011) and GaBi (PE International GmbH, 2007) are able to model a pack across its different life cycle phases. The Cambridge Engineering Selector, CES, Eco Audit Tool (Granta Design Ltd, 2011) can also be used to assess the environmental impacts of a pack. However, unlike the previous comprehensive LCA software, which requires a detailed and time consuming inventory development, it can provide a quick estimation of the environmental impacts of a particular material used in the pack's manufacture.

The 15 tools reviewed in this section were then combined with the results of the previous section 4.3. This gave a sample of around 40 tools which were then assessed against four key criteria considered most relevant to the required features of a sustainable packaging design tool. These were: Sustainability Considerations (Which of the three key pillars of Sustainability, Environmental, Economic and Social, were considered by the tool), Life Cycle Approach (What life cycle stages were considered), User Guidance (Which of the 5 guidance criteria listed were output to the user) and User Inclusiveness (of the user groups listed, how many would the tool be useful and accessible to). The results of this review are provided in Table 4.4 and illustrated diagrammatically in Figure 4.3.

Table 4-4: Results of the assessment of 40 design tools from section 4.3 and 4.4

Assessment Criteria				
Sustainability Considerations:	**En**	**En & Ec**	**En & So**	**En, Ec & So**
Environmental (En), Economic (Ec), Social (So)	20	13	6	1
	50.0%	32.5%	15.0%	2.5%
Life Cycle Approach:	**None**	**C2G**	**G2C**	**C2C**
Full (C2C), Cradle to Gate (C2G), Gate to Cradle (G2C), None	16	6	11	7
	40.0%	15.0%	27.5%	17.5%
User Guidance:	**1**	**2**	**3 or 4**	**all 5**
Descriptive, Selective, Prescriptive, Assessment, Comparative	21	18	1	0
	52.5%	45.0%	2.5%	0.0%
User Inclusiveness:	**Specialist**	**Business**	**SC**	**SC&C**
Specialist, Bussiness, Supply Chain (SC), Supply Chain & Consumer (SC&C)	24	11	5	0
	60.0%	27.5%	12.5%	0.0%

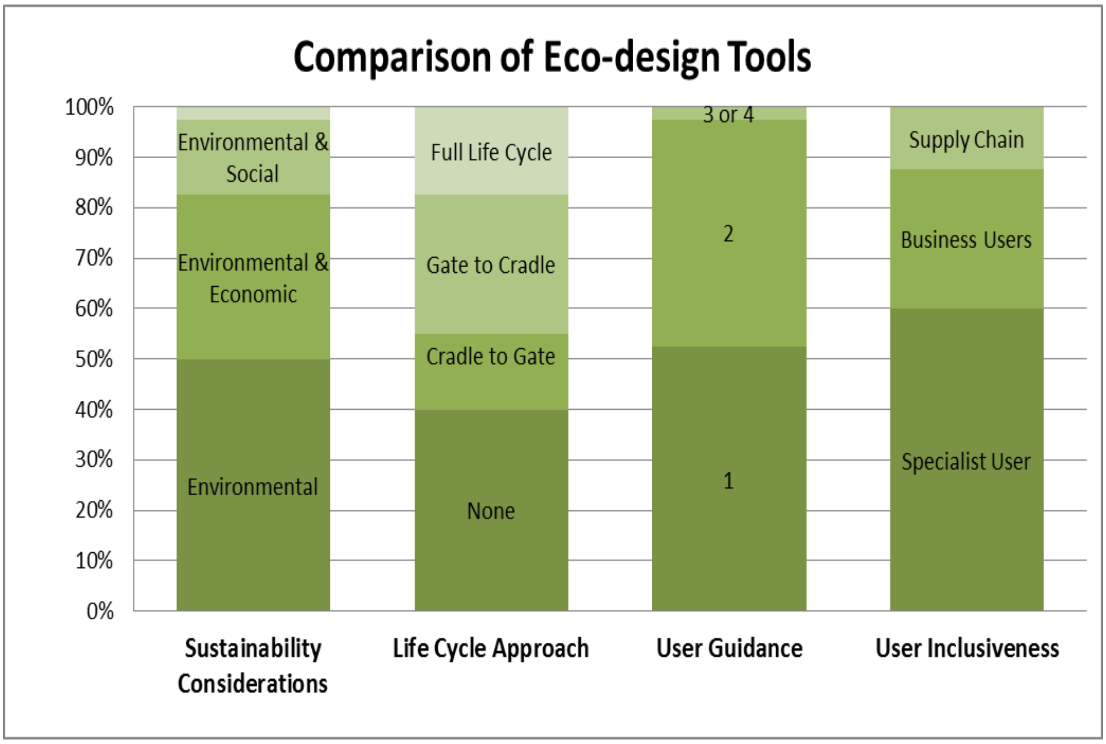


Figure 4-3: Results of eco-design tool review showing percentage comparisons.

4.4.1 *Summary and discussion of eco-design tool review.*

As would be expected from the 'eco-design' inclusion criteria applied to this study, all the tools reviewed considered environmental impacts to a greater or lesser degree. However just half went beyond this to consider a further economic or social factors and only one of these considered all three. This is indicative of the inherent difficulty in balancing the varying needs of the three 'pillars' of sustainability in a single integrated tool in a robust and meaningful way.

It was also found that 40% of tools did not follow a Life Cycle approach and only 17.5% provided a full cradle to cradle support. Finally the tools tended to be targeted at specialist and professional business users with the consumers and customers generally not considered. A more detailed discussion of this review can be found in the conference paper presented at CIRP in 2011 (Colwill *et al.*, 2011), a copy of which is provided in Appendix 2.

4.5 Review of biopolymer packs in commercial applications

To understand how the design and use of biopolymers packaging has evolved, an online review of published announcements for new product launches in bio-derived packaging was undertaken. This included searching the websites and press archives of all the main biopolymer manufacturers, associated trade press and the key industry bodies, associations and institutes for the environment, packaging and plastics industries, dating back to 2004. It is an expected and an accepted limitation of this review that as a material becomes established, i.e. first generation bio-polymers such as cellulose film and foamed starch chips, they will probably become less noteworthy of press comment and so the frequency of announcements will decline even if the use of this material or packaging actually increases. Furthermore the study considers launch activity only, not its on-going sales, and so should not be viewed accumulatively. This is because the packaging may have been withdrawn from the market soon after its launch (Byrne, 2010).

From the results of the study presented in Table 4-5, there would appear to be a significant bias towards the use of biopolymer packaging for food and drink products as these account for the majority of new pack introductions. In terms of the different packaging formats, flexible films and bags appear to be the dominant pack type. This trend would be supported by the clear synergies of a natural biodegradable ‘plant’ based polymer for use as food packaging, both in terms of origin and also end of life management where the majority of plastic films are not recyclable due to the mix of different polymer types.

Table 4-5: New products launched in biopolymer packaging between 1990 and 2009. (Colwill, *et al.*, 2011)

Product Group	Bio-derived Polymer Materials					Pack Types			
	Cell-ulose Acetate	Starch	PLA	PHA	Sub Total Material	Films and Bags	Semi-rigid / Thermo-forms	Rigid	Foam
Food	4	2	31	0	**37**	28	9	0	0
Drink	0	0	8	0	**8**	0	0	8	0
Cosmetics	1	0	2	1	**4**	1	0	3	0
Distribution	0	3	1	0	**4**	0	0	0	4
Electronics	0	0	0	0	**0**	0	0	0	0
Other	1	5	3	0	**9**	7	2	0	0
Total	6	10	45	1	**62**	36	11	11	4

When the numbers of new introductions are plotted against their launch dates, a picture begins to emerge of gradual annual growth in new biopolymer applications. This trend is shown by the lower line plotted in Figure 4.5. However, this only shows the frequency of product launches and does not consider the size or significance of each new introduction. The detail of information, provided in a typical company announcement or press release, is insufficient to ascertain an accurate figure regarding the amount of bio-derived polymer being used. So a simple weighting factor was applied based on five easily assessable key criteria: Brand awareness, Company size, Launch market size, Potential market size and Application complexity.

For the first four of these five criteria a weighting factor of 1x for local, 3x for national or 5x for global was applied. For the fifth criteria, 'Application Complexity', a weighting of 1x for low complexity, 3x for medium (thermoformed/laminated), 5x for high complexity (injection moulded, blown, high barrier) was used. Once applied the sum total was divided by five to a final value of between 1 and 5 for each application. When this data is re-plotted using the weighting factors described above, it shows a much sharper growth curve particularly during the last two years, as shown by the upper line in Figure 4.5.

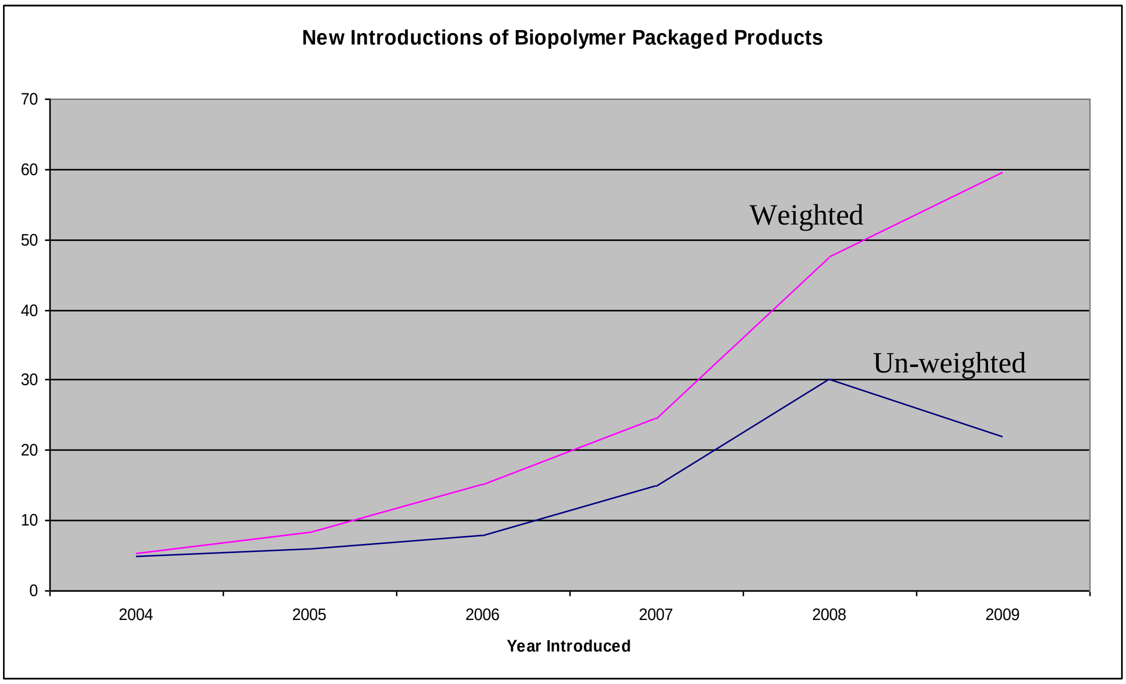


Figure 4-4: Growth in BDP Applications (weighted and un-weighted) 2009 based on six months recorded data, doubled for full year. (Colwill, et al., 2011)

This sharp increase indicated by the weighted results could indicate that biopolymers are entering a new accelerated growth phase, which could lead to higher growth levels than previously forecasted using other data sets such as; BDP production capacity investments, (Shen *et al*, 2009) which predicts growth by 2020 to reach 3.5 Mt capacity and earlier projections published by Crank et al. (2005) of between 2.5mt and 4.17Mt. In addition, when the two graphs are compared it suggests that in addition to a general increase in use, these new bio-derived polymers are gaining wider market acceptance, moving from niche, synergetic applications such as organic, fair-trade and health food products to mainstream, high profile brands.

4.6 Chapter Summary

This chapter has provided an overview of eco-design methods, guides and tools used within the commercial sector, particularly to support the design and development of sustainable packaging. The results of this review highlighted the requirements for a novel sustainable pack design decision support tool which will be validated through industry consultation and discussed in more detail in later chapters. However, the six key features that have been identified are listed in Table 4-6. The key elements of these features that have been shown to be absent or inadequately provided for in existing tools are highlighted in bold and underlined.

Table 4-6: Key features, requirements and intended users of the tool.

Feature	Requirements
Full Life Cycle Perspective	Should consider performance across the **whole** life cycle, cradle to cradle.
Sustainable Focus	The tool should consider all three pillars of sustainability: **Social** as well as Environmental and Economic.
Strategic and Tactical	The tool should support **strategic** decision making looking at future performance as well as current properties and performance.
Holistic and Inclusive	Should be usable and provide guidance across the whole supply chain, including consumers.
Total Stage Support	Should provide support at **each stage** of the design / development process through a series of individually targeted but connected tools.
Feedback	Tool should provide **feedback** which allows progress to be measured and improved.

Chapter 5 Biopolymers and Sustainability Research

5.1 Introduction

This chapter presents a review of the literature related to the use of biopolymers in the design of sustainable packaging. It begins with an overview of the key environmental impacts of plastic packaging followed by a critical review of published life cycle assessment studies of biopolymers and biopolymer-based packaging. This is followed by a review of current research on incorporating the social dimension into an LCA as a step towards sustainability assessment rather than just eco-assessment. Finally consideration is given to the difficulties of multi-criteria decision making within the sustainable design process, and how the use of Analytic Hierarchy Process (AHP) and the Business Score-Card (BSC), developed by Kaplan and Norton at Harvard, can be used to support that process.

5.2 Plastic Packaging and the Environment

Plastic packaging can impact the environment at various stages during its life cycle, from the extraction of raw materials to end of life management. A typical lifecycle of a plastics package made from either conventional polymers or biopolymers is shown in Figure 5-1. The life cycle of biopolymers and conventional polymers differ mainly in the production and end of life stages and these are shown separately: green for bio; blue for conventional. Where the life cycle stage is common to both purple is used. Shades of red denote environmental impacts, whilst the depth of shading indicates the severity of the impact. The following section reviews the impacts at each life-cycle stage in more detail.

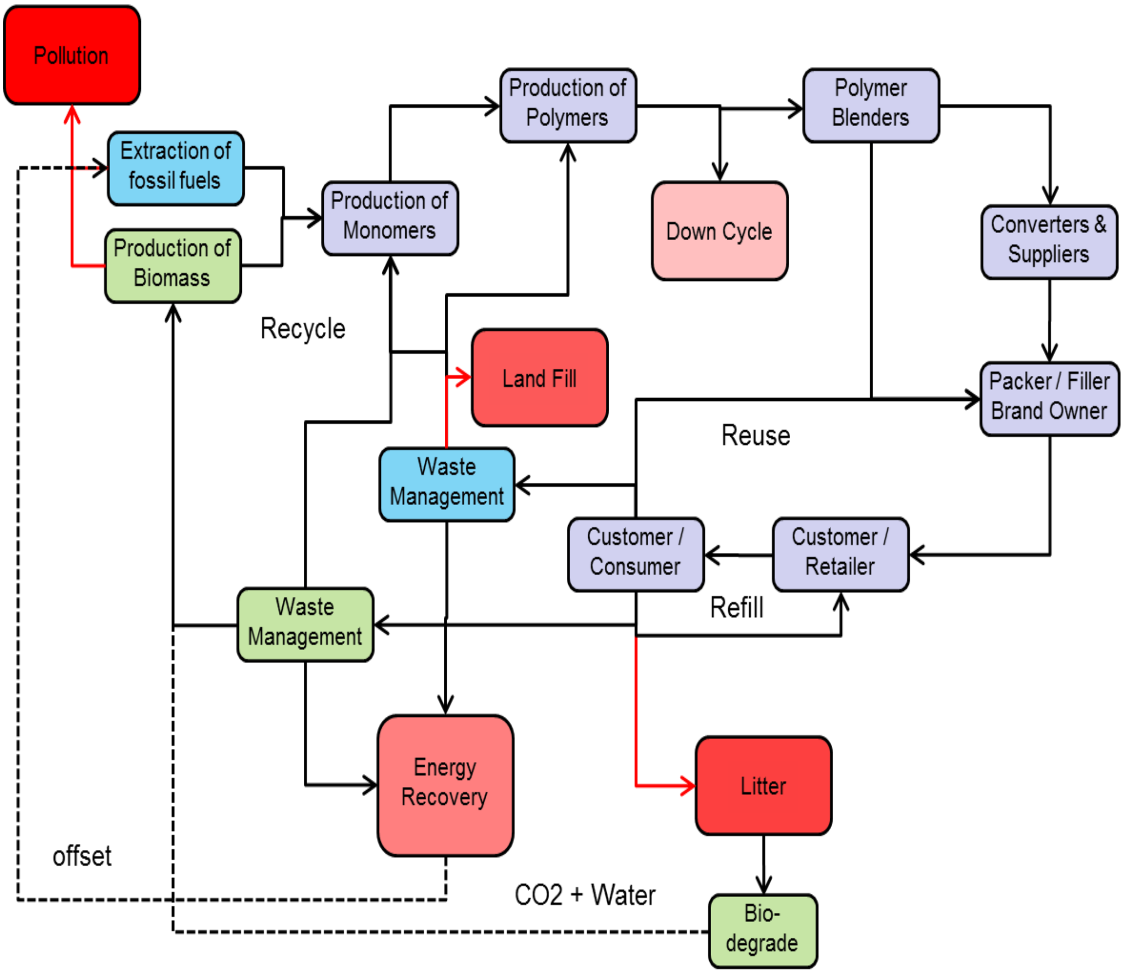


Figure 5-1: Life cycle of plastics packaging (conventional and bio-polymers)

5.2.1 *Extraction and Production*

For the conventional polymers this first stage of the life cycle covers the exploration and extraction of the fossil fuels up to the production of the polymer resin, whilst for the bio-polymers the production of the biomass to the manufacture of the bio-polymer resin is reviewed.

5.2.1.1 Conventional Polymers

Conventional polymers are currently produced from all three of the major fossil fuel types; coal, oil and gas, although it is crude oil which has been the major source to-date, due largely to the huge volume of crude oil that is processed by the petroleum industry for transport fuels. Ethylene, the precursor for PE, could be argued as being a by-product of the petroleum process, making it a virtually free and cost effective resource.

As the main driver for fossil fuel exploration and extraction is primarily for energy, it could be misleading to directly attribute the full impacts of the crude oil used in plastics production, currently around 4% (American Chemistry Council, 2009). However it would also be inaccurate to ignore it on this basis as in addition to the raw material feedstock, further fossil fuels are used for the additional energy required during the production process, transportation and conversion.

Exploration:

Of the 900,000 oil and gas wells currently operational in the USA over 3.5 million have been drilled, the cumulative effect of this exploration and subsequent extraction is therefore much higher than the annual production figures might indicate (Otton, *et al.*, 2002). Each drilling operation will require infrastructure, land modifications, facility construction and energy use as well as generating a number of environmental pollutants such as hydrocarbon emissions (methane and oil), saline water and dissolved toxic metals and naturally occurring radioactive materials (Kharaka & Dorsey, 2005). As the search for new resources pushes exploration into more extreme and environmentally sensitive areas such as deep sea and Polar Regions, so the impacts increase from both the intended and unintended consequences of exploitation (Ecotopia, 2000). Furthermore the exploitation of the lower grade resources such as ‘fracked’ gas, oil sands and brown coal have a higher environmental impact for each unit of energy or plastic produced compared to the higher grade resources such as US sweet crude or Saudi oil and gas (U.S. Environmental Protection Agency, 2008).

Extraction

Many of the environmental impacts associated with extraction of oil and gas are the same as with exploration, however over the life of an active well, these environmental impacts are going to have a greater cumulative impact. In addition the risk of spillage or unintended emissions increases as does the quantity of waste, such as salt water, that needs to be disposed of. Recently examples of the environmental impact of oil production have been notable, such as the Deepwater Horizon disaster in 2010 which released around 5 million barrels of crude oil into the Gulf of Mexico; the largest oil spill in human history (Hoch, 2010). A major factor in this was the delay in capping the well to stop the release of oil due to it being situated in such deep water.

The environmental impacts associated with natural gas have generally been associated with its use (combustion); CO_2 emissions and climate change, rather than with its extraction. However a relatively new extraction technique called ‘fracking’, has raised concerns regarding the extraction of natural gas from shale using this method. Large amounts of water are required for this process and a cocktail of potentially harmful chemicals are added which could contaminate ground water supplies. In addition to water use contamination and disposal, other concerns include the triggering of earthquakes and use of land (Linley, 2011).

For coal, there are two main forms of extraction, surface mining and underground mining. Surface mining is the most environmentally damaging of the two and accounts for around 40% of current global coal production. First the seam of coal has to be exposed by removing the surface soil and rock, this overburden is usually dumped on land adjacent to the mining area. Once the coal is removed a new section is prepared with the overburden used to fill the old open pit, this is often referred to as strip mining. Other examples include the removal of mountain tops to expose the coal underneath with the overburden dumped in adjacent valleys covering streams and bio-rich habitats. As with oil and gas, methane emissions can result as well as other pollutants such as heavy metals etc.

Production

Conventional polymers are produced through a polymerisation reaction of a particular monomer, such as ethylene to make polyethylene, which is the same principle used to make bio-PE from bio-ethylene. For conventional polymers the ethylene is obtained from the processing of crude oil by cracking, a process which splits the crude into its different hydrocarbon fractions. This process is energy intensive and produces a range of other hydrocarbon fractions. Whilst the ethylene might be considered a by-product of the petroleum and diesel manufacturing process some environmental impacts, such as from VOC’s, should be in part attributable to the monomer production. The subsequent polymerisation will depend on the polymer being produced, whilst most are exothermic, they consume resources such as water, energy and materials within the processing plant. Other polymers such as PVC require additional chemicals such as chlorine which will have further environmental impacts, mainly from energy use but also from the potential hazards of handling chlorine gas etc. and the environmental impact if released into the environment. In summary the main environmental impacts and sustainability issues associated with conventional polymers at this stage of their life cycle include:

- Consumption of finite resources (Fossil Fuels).
- Emissions of Green House Gas (GHG) and Volatile Organic Compounds (VOC), these would include CO_2, SO_2, and Hydrocarbons.
- Air pollution (VOC's, SO_2, CO)
- Water contamination (Heavy Metals, Salts, VOC's)
- Use of land and water resources
- Use of other material resources for construction and engineering.
- Destruction/Loss of natural habitats
- Heavy metal, radioactive, and other toxic emissions
- Increased risk of major environmental disasters from oil and gas leaks.
- Ground water contamination from new extraction methods

This is not an exhaustive list and will vary in degree and range on a case by case basis.

5.2.1.2 Biopolymers

The initial stages of the biopolymer life cycle is a little more complex as there are many different feed stocks that can be used in their manufacture. In most cases the environmental impacts will be largely weighted towards the production of the feed stock used although investigation into non-food competing crops is underway.

Feedstock Production

The majority of biopolymers currently used as packaging are almost exclusively produced from starches and sugars obtained from agricultural crops such as corn, sugar cane/beet or oil seed crops. Other feed stocks, such as cellulose, are obtained from less intensively farmed sources (trees, grasses) or from agricultural waste (straw, corn stovers). More recently algae and bacteria have been bio-engineered to produce specific materials in their cells such as PHA, sugars or ethanol, which can then be harvested. As with any intensive farming operation, the environmental impact can be significant and just as fossil fuels are a finite resource, so land, water, fertilisers are also limited. Whilst the use of certain feed-stocks may reduce the environmental burden, there is still a requirement for energy (fossil fuels) in harvesting, transport and processing them. Obviously the environmental impacts at this stage can vary hugely based on the type of feed-stock used (crops/waste), the type of crop and farming method (Corn - mechanised and intensively farmed or sugar cane – manual and low intensity farming), and the amount of processing required (transport, energy, infrastructure, waste).

Whilst many LCA field to gate studies have indicated an environmental benefit from biopolymers, others have shown there to be negative impacts (Tabone, *et al*., 2010). In addition to the negative environmental impacts, another major concern has been the consequences of bio-polymers competing for resources with food production, although it is small compared to the bio-fuels market with which it also both competes and benefits from in terms of scale and production efficiency (Altprofits, 2009). As with conventional plastics, there are similar difficulties in ascribing the impacts associated with the production of feedstock used to manufacture biopolymers, where other products, such as ethanol or animal feed, are also produced.

5.2.2 *Manufacture and Distribution*

For conventional and biopolymers this stage includes the blending and conversion of the polymers into a pack, its filling and distribution to the customer/retailer. Whilst the types of impacts may be quite similar between conventional and biopolymers during these stages the level of impact may vary depending on distances shipped, levels of waste, and energy used. Due to the widespread availability of conventional polymers and the more restricted manufacture of biopolymers, distribution may be a key factor at this stage with its associated use of fossil fuels and CO_2 emissions.

The conversion process of plastics into packaging usually involves heating the polymer to extrude or mould it into shape and to seal it. As biopolymers generally have a lower melt point than conventionals there is a potential to reduce the amount of energy used at this stage. However, other material properties may result in the need for increased pressures, reduced cycle times, higher waste levels etc. (Colwill & Rahimifard, 2013) It is therefore likely that the greatest environmental impacts at this stage of the life cycle will be energy use and the related GHG emissions of mainly CO_2 and possible additives used in the processing of the polymers such as plasticisers.

The distribution of the packed goods is likely to be the same for both of these polymer groups, although due to the lower performance and barrier properties of bio-polymers to water, oxygen, temperature etc. There may be a reduction in shelf life or increase in damage which could result in greater product waste although this would have to be assessed on a case by case basis. Furthermore these potential impacts can be limited or even avoided by ensuring the correct specification and handling of the bio-plastic packed products.

5.2.3 *Retail and Consumer Use*

The sustainability impacts of the different polymer types during this stage can be minimised by ensuring that the polymer with the properties most suited to the required functionality is selected. Avoiding increased damage and spoilage would be the main priorities which largely fall into two categories protection and preservation. In terms of protection, different polymers will have a range of properties that can be optimised for a particular purpose, impact strength, puncture resistance, compression strength, scuff and scratch resistance etc. and these may vary according to temperature i.e. Biopolymers are more likely to become brittle at lower temperatures and to be less resistant to higher temperatures (lower melt points), although new materials and blends are being produced which are extending the range of biopolymer applications.

Preservation is the other key performance area that is particularly applicable to bio-polymers, which are often used for food packaging due to the obvious synergies. One of the major advances in food packaging has been the development of polymer based packaging enabling high performance barrier properties and lightweight minimal packaging to preserve and extend the shelf life of food products, so reducing wastage. Whilst conventional and biopolymers can be combined or coated with other materials to improve their barrier properties, these often reduce their bio-degradability or recyclability. For some applications the lack of moisture barrier in some bio-polymers can be advantageous offering a sealed clean package that still allows the product to breathe, this may be particularly useful for baked goods and fresh whole produce.

One of the disadvantages of polymers comes from their diversity and complexity without any obvious noticeable difference to the consumer. This often leads to confusion as to how the package may be finally disposed of e.g. composted, recycled. Whilst a labelling / marking system has been implemented with some success, it is often beyond many consumers’ to use the information provided effectively. One approach to simplification was the standardisation of materials for certain product/pack applications e.g. PE for milk bottles, PET for drinks bottles, however biopolymers have further complicated this by adding another material type which is difficult to separate.

5.2.4 *End of Life Management*

It is widely accepted that in a world with increasing demand and diminishing availability, the preservation of resources is essential for the continuation of our current societies and global development. One option towards a more resource efficient world is to reduce our waste, and in this context, burying packaging in landfills is no longer considered a sustainable solution. As a result alternative End-of-Life (EoL) management options have been developed for post-consumer and industrial waste of which plastics packaging is a major component. Whilst some of the options such as recycling are common to both conventional and biopolymers, the specific methods used can vary and so these will be considered separately.

5.2.4.1 Conventional Polymers EoL management options

Conventional polymer packaging waste, where possible, should be recycled. Waste occurs at various points along the supply chain, usually becoming more widely dispersed and contaminated as it progresses. Waste generated during manufacturing and conversion is usually easier to recycle as it is less contaminated, more controlled, contained and generated in sufficient quantities to be economically viable to collect/recover. Packaging waste generated after it is filled will be more highly contaminated by the product and additional packaging materials such as labels and therefore will require more intensive processing, but still has the advantage of being relatively controlled and concentrated.

Finally there is municipal waste generated by the consumer and small businesses. Here the waste may be contaminated, contain a mix of materials and be widely dispersed. Even if pre-sorted there can be no absolute guarantee of purity, therefore the controlled sorting and separation municipal waste post collection is an essential part of the recycling process. For waste that cannot be recycled, a range of technologies are used to recover some value from it such as incineration (energy recovery), gasification/pyrolysis (chemical and energy recovery). However, even in countries with developed waste management systems, plastics will still go to landfill. Table 5-1 provides an overview of different polymers, their common packaging applications and the end-of-life processing methods available for their recovery.

Table 5-1: Polymers: Key packaging applications and end-of-life management options.

Key w wholly applicable p partially applicable - unknown *BE – produced from bio ethylene			**Packaging Applications**				**End-of-Life Management**			
			Flexibles – films, bags…	Semi Rigid – ThF, SBM - Trays, bottles…	Rigid – Inj. Moulded - caps, devices…	Foamed – Moulded, extruded – Filler, pads…	Compostable - Home	Compostable - Commercial	Bio-degradable	Recyclable
Fossil Derived - Conventional Polymers	**PE**	**Polyethylene**	w	w	w	w				w
	LDPE	Low Density PE	w			P				w
	LLDPE	Linear Low Density PE	w							w
	HDPE	High Density PE	w	w	w	w				w
	PP	**Polypropylene**	w	w	w	w				w
	OPP	Orientated PP	w							w
	BOPP	Biaxially Orientated PP	w							w
	PS	Polystyrene	w	w	w	w				w
	PET	**Polyethylene Terephthalate**	w	w						w
	APET	Amorphous PET	w	w						w
	PETg	PET Glycol		w						w
	CPET	Crystallised PET	w	w	w					w
	OPET	Orientated PET	w							w
	PVC	Polyvinyl Chloride	w	w	w					w
	PA	Polyamide - Nylon	w	P	P					w
	PVA	Polyvinyl Alcohol	w	P			P	P	P	-
Mixed	PVC	Polyvinyl Chloride – BE*	w	w	w					w
	PET	Polyethylene Terephthalate – BE*	w	w						w
	Blends	Starch blends (FD copolymers)	w	w	P	w	P	P	P	
	Blends	PLA blends (FD copolymers)	w	w	P		P	P	P	
	Blends	Conventional FD/BD blends	w	w	P			P	P	
Fully Bio-derived	RC	Regenerated Cellulose	w				P	w	w	w
	CA	Cellulose Acetate	w				P	w	w	w
	PE	Polyethylene – BE	w	w	w	w				w
	PP	Polyproylene – BE	w	w	w	w				w
	TPS	Thermoplastic starch	w	w	P	w	P	w	w	w
	SA	Starch Acetate	w				P	w	w	w
	PLA	Polylactide - Poly Lactic Acid	w	w	w		P	w	w	w
	PHA	Polyhydroxyalkanoates	w	w	w		p	w	w	w

5.2.4.2 Biopolymers EoL management Options

The End-of-Life management of products manufactured from biopolymers should be considered, as with all waste streams, in the context of the waste management hierarchy. Historically, the biodegradable or compostable nature of many biopolymers has been seen to provide an end-of-life solution without other options being considered, however there is now greater realisation of the need to recover the maximum value from all materials at End-of-Life.

Alternative End-of-Life management scenarios are emphasised on the life cycle diagram shown in Figure 5-2. Elimination or reduction of waste at source is the preferred option within the waste management hierarchy, and requires proactive measures to be taken during the product design stage, prior to product manufacture. Reuse requires effective recovery of used products, and may be achieved on a micro (within the home of a single consumer), or macro (within a local council) level. Recycling is shown here as a closed loop system, whereby recovered products are used to provide an alternative source of polymer material, thus replacing the need for the generation of virgin polymer.

Alternatively, down-cycling or, less commonly, up-cycling may be achieved, in which recovered products are used to provide a new material resource for lower or higher grade applications, respectively. Composting is only available for polymer materials with adequate biodegradable properties, and results in the return of some nutrients to the soil, thus closing the loop where renewable raw materials are concerned. Finally, energy resources may be recovered by a range of processing technologies and, as a last resort, waste may be disposed of to landfill, with loss of all material and energy resource from the supply chain.

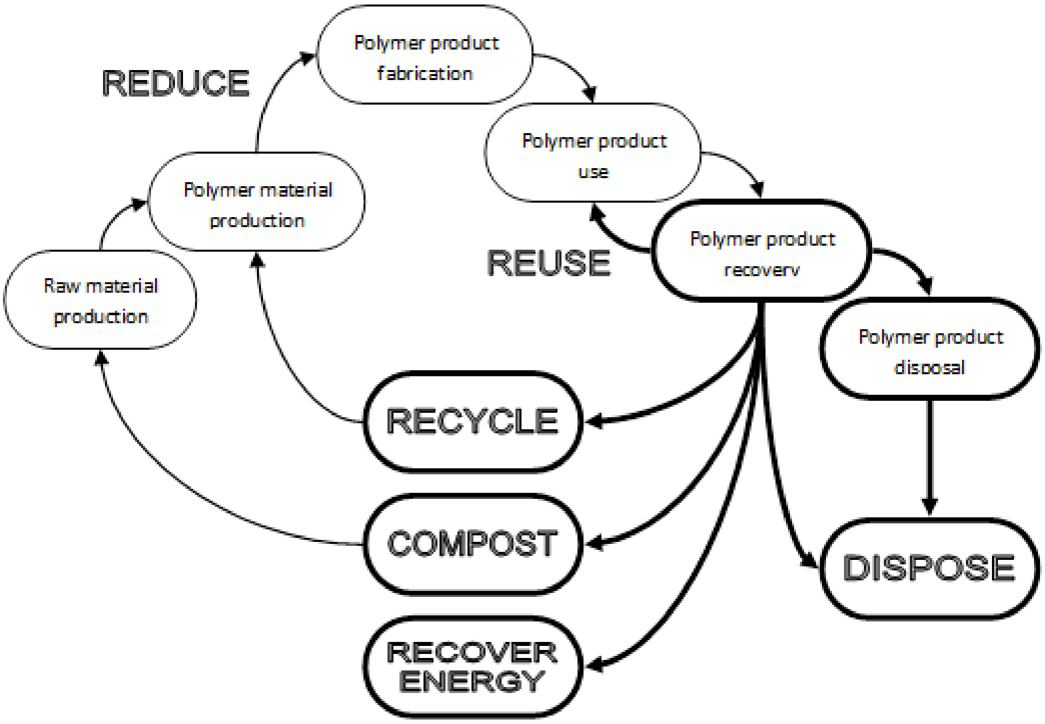


Figure 5-2: Product life cycle diagram highlighting alternative end-of-life management scenarios for bio-polymer packaging, based on the waste management hierarchy.

For each level of the waste management hierarchy identified in Figure 5-2, alternative processes have been reviewed in order to determine the issues specific to the processing of waste from biopolymer packaging. The issues associated with reduction of waste and reuse of packaging was found to be generically similar to those associated with packaging waste made from conventional materials. These proactive approaches to waste management are more concerned with the way in which packaging is designed and used, and are addressed in the early stages of the life cycle. Of more technical interest are the issues related to reactive waste management approaches, concerned with the processing of post-consumer waste streams. The opportunities and challenges associated with recycling, composting and energy recovery are often directly related to the physical and chemical properties of the bio-polymer materials. In addition, pragmatic concerns regarding waste collection, sorting and contamination were found to play an important role at these levels of the hierarchy.

i) Reduction of Biopolymer packaging waste

The first priority in the waste management hierarchy is the reduction of waste at source. This can be achieved through proactive means, during the design of packaging. In order to reduce waste arising from packaging, opportunities for light-weighting or simplification of packaging design might be considered. This approach has been widely adopted within the packaging industry over recent years. Furthermore it is necessary to consider how substitution of conventional packaging materials with bio-polymers might affect the overall volume, or mass, of waste produced. This consideration should extend to include waste production throughout the packaging life cycle, including in the production of raw materials, production of bio-polymer materials and production of packaging products. Since one of the primary functions of packaging is to protect goods, thus preventing waste during transportation and storage, the performance of biopolymer based packaging in fulfilling this function must also be considered relative to conventional packaging solutions. Reduction of waste at source should be maintained as an objective in the development of more sustainable packaging, regardless of the reactive waste management approaches adopted for the processing of post-consumer packaging waste.

ii) Reuse of Biopolymer packaging waste

Primary packaging is generally designed to be single-use and as such is characterised as being low-cost, designed for disposal. The reuse of primary packaging does occur in some circumstances, but is arbitrarily driven by individual consumer behaviour and circumstance and therefore cannot be guaranteed as a feature of the product life cycle. Examples of common reuse scenarios observed for primary packaging include:

- Refilling of plastic drinks bottles
- Reuse of plastic carrier bags as carrier bags
- Reuse of plastic carrier bags as bin liners
- Reuse of plastic containers and cartons for storage

In considering the application of biopolymers in primary packaging, the impact of these new materials on opportunities for reuse should be considered as a factor influencing, but not defining, the environmental impact of primary packaging products. The substitution of conventional packaging materials may have an effect upon the robustness or durability of primary packaging products, thus influencing the extent of reuse available to consumers. Maximising the reuse of primary packaging can also be influenced by the design of packaging products. Opportunities for reuse of biopolymer packaging are more likely to be realised for secondary or tertiary packaging products, used during transportation or storage. For these products, ownership may not be transferred to the individual consumer, but may be retained by, for example, the haulier or manufacturer. This retention of ownership introduces an economic incentive for reuse, and consequently supports the inclusion of reuse requirements in the design of secondary packaging.

iii. Recycling of Biopolymer packaging waste

The recycling of post-consumer bio-polymer waste has largely been ignored due to the limited amount of material available in the waste stream and the emphasis that is placed on its biodegradable properties by the manufacturers, which have encouraged consumers to compost or dispose of the materials with the organic waste. Biodegradable biopolymers such as starch degrade rapidly after disposal, particularly in damp conditions, which would make mechanical recovery and separation extremely difficult. Cellulose can be recycled with paper, cellulose is categorised by the UK Environment

Agency alongside paper and board for recovery purposes, becoming incorporated into the paper pulp. Independent laboratory tests have demonstrated that approximately 50% of a 28µ Clarifoil film (cellulose acetate film) can be successfully re-pulped along with paper and board to produce recycled paper (Clarifoil, 2013).

Synthesised biodegradable biopolymers such as PLA, PHA and PHB are now achieving greater commercial success and as a result concern about the impact it will have on the current plastics recycling infrastructure and contamination of the recycling stream has been raised. While current waste management systems for PLA are still evolving, NatureWorks, the leading manufacturer of PLA in the United States, has evaluated several different sorting technologies to sense and sort PLA from other plastics.

Near-Infrared (NIR) is the industry's preferred plastics sorting technology because it can accurately identify the many different polymers already in use today (different polymers reflect an identifiable specific light spectrum). Natureworks claim that testing on widely-used present-day technology has shown that Ingeo™ (A brand of PLA) can be identified in the mixed waste plastics stream with very high accuracy, (NatureWorks LLC, 2013d). Titech, a manufacturer of near-infrared sorting systems, has demonstrated the ability of its products to eject concentrated amounts of PLA in a PET sorting operation. In one test a 3,000lb bale of plastic was infused with 0.75% Ingeo™ product and using NIR, sorting 453 ppm Ingeo™ detected in the flake; a 94% accuracy. This flake was then washed & extruded into sheet film. The results showed "no difference in clarity or colour versus the control flake batch" (TITECH, 2013).

Other manufacturers have achieved sorting efficiencies as high as 96-99%. This is consistent with other plastics considered contaminants using the PET flake sorting technology. In a report published by the Waste Resources Action Program (WRAP) it was stated that NIR systems can effectively remove Ingeo™ bioplastics and carton board from a mixed packaging stream (WRAP, 2008).

Black Light Illumination: Natureworks have also partnered with bottled water brand, Primo, to test the feasibility of sorting using black light illumination in recognition of the fact that not all of today's recyclers have the latest technology in sorting equipment installed and a cheaper option needed to be identified. Natureworks reported that the initial results are promising. “A light signature was injected inside the preform for a Primo water bottle. Under a normal black light, the bottle fluoresces allowing for visual separation of plastics. This process has been tested at two major recycling facilities with excellent results" (NatureWorks LLC, 2013d).

Having separated PLA from the waste stream the next step is to recycle it; this can be achieved in two ways, mechanical or chemical separation. The most exciting of these is the chemical separation which converts the PLA back into its Lactose monomer. GALACTIC, a leading global supplier of lactic acid and lactates, created a new division called LOOPLA, which retrieves Lactic Acid from various kind of PLA waste through chemical recycling (hydrolysis). This retrieved Lactic Acid can be used for new industrial applications, namely new PLA production ensuring therefore a true Cradle-to-Cradle approach, (European Bioplastics, 2009). Using hydrolysis, PLA resin from the bottles can be recycled indefinitely with virtually no need to add virgin polymer. Since 2004, NatureWorks has recycled more than 17 million pounds of off-grade Ingeo™ natural plastic at its Blair site, Nebraska, using this process (GALACTIC, 2009).

Bio-conventional polymers produced from bio-ethylene are identical to their conventional fossil-derived counterparts and include the polymers groups PE, PP, PET and PVC. These biopolymers can thus be recycled and used interchangeably with conventional polymers and so, despite their very recent introduction, are already at a scale where they can be recycled. However, only two of these conventional plastics (PET and HDPE) are actually being recovered and recycled at the post-consumer level in any significant quantity (Environmental Protection Agency, 2008)

iv. Composting of biopolymer packaging waste

To be composted the biopolymer must be biodegradable, which excludes the bio-conventional polymers. For the others, in order to be effective as a packaging material, most are modified to improve their stability and protective/barrier performance, which can increase their resistance to biodegradation, however under the right conditions, temperature and humidity, and in the presence of microorganisms, most biodegradable biopolymers will eventually compost. For example PLA, a repeating chain of lactic acid, undergoes a 2-step degradation process. First, the moisture and heat in the compost pile split the polymer chains apart, creating smaller polymers, and finally, lactic acid. Microorganisms in compost and soil consume the smaller polymer fragments and lactic acid as nutrients. Since lactic acid is widely found in nature, a large number of organisms metabolize lactic acid. Organic materials composted in suitable aerobic conditions will produce carbon dioxide, water and humus, a soil nutrient (Natureworks LLC, 2013b).

v. Energy recovery from biopolymer packaging waste

With mixed waste, usually the most sensible disposal option is to incinerate at high temperature with energy recovery. Fully combusted most biopolymers produce only CO_2 and water plus, in some cases, a little non-toxic inorganic ash. Most have a positive calorific value making it viable to recover the energy for heating purposes.

vi) Landfill of Bio-polymer packaging waste

This is the least preferred option for bio-polymers as the majority of which will not decompose readily in those conditions, and the anaerobic decomposition produces methane which is over 30x more powerful, as a greenhouse gas, than CO_2.

5.3 Biopolymer ‘packaging’ and Life Cycle Assessments

Life cycle assessment is a well-established methodology commonly used to quantitatively evaluate the environmental impacts of products and processes during all or selected stages of their life cycle (International Standards Organisation, 2006). This method has been applied to the evaluation of biopolymers in order to establish their environmental benefits, either commercially for the purpose of producing environmental product declarations, or in academic studies to promote greater understanding and direct future research and appropriate use of these materials. Although international standards (ISO14040/44) have been developed for conducting an LCA, there remains considerable variability in results due to the flexibility allowed in the setting of the studies functional unit, scope and boundaries.

In order to establish a current consensus on the environmental benefits of biopolymers, and so better understand how and when they may be best used in packaging applications to achieve the greatest environmental benefits, a systematic review of published LCA studies from academic and commercial literature was conducted, spanning a time period between 1997 and 2012. Twenty five studies were identified and were reviewed in terms of various criteria that included:

- Scope:
  - Life cycle stages – which life cycle stages were included?
  - Environmental impacts – which environmental impact categories were evaluated?
- Quality:
  - Data quality – how reliable was the data?
  - Independence – how was the study funded?

The results from this review are summarised in figure 5.3.

Partial LCA: These studies focused on biopolymer production. These cradle-to-gate studies were largely performed or funded by biopolymer producers such as NatureWorks LLC, Novamont S.p.A and Metabolix inc. and based on data from industrial processes (Kurdikar, et al., 2001); (Vink, *et al*., 2003); (Vink, *et al*., 2007); (Razza, *et al.*, 2009),. Because of the potential competitive advantage to a company in keeping its production processes secret, the confidential information used in these studies resulted in there being very little detail in the published results.

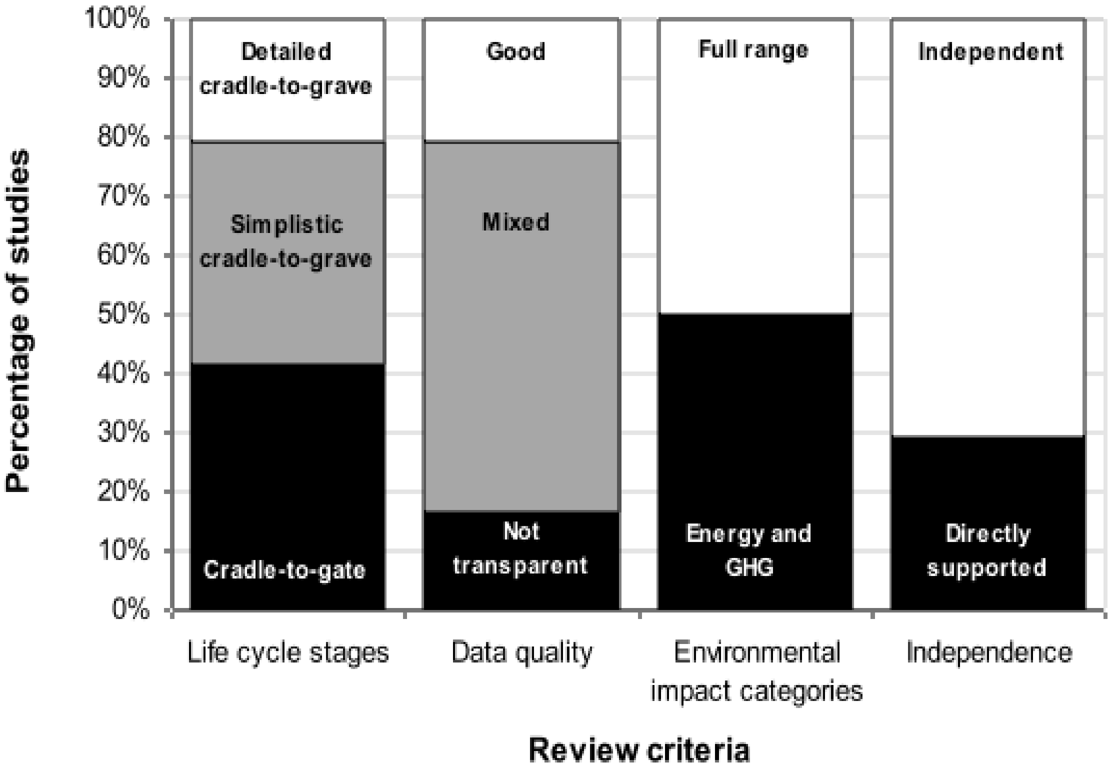


Figure 5-3: Review of LCA studies against review criteria 2009

Full LCA studies: The availability of published cradle-to-grave studies in which all life cycle stages were considered is limited. More often these studies were extended cradle-to-gate studies where simplistic assumptions had been made regarding the use and end-of-life stages such as: Johansson, (2005); Harding *et al*., (2007); and Madival *et al.*, (2009). Whilst the generation of scenarios based on simple assumptions may prove useful in indication potential environmental impacts, the results of such studies should be treated with caution, and could be misleading if taken out of context.

Data Quality: In studies where primary sources of data had been used, the quality was reasonably good, however some studies were not open regarding their source of data and so cannot be easily assessed. The majority of studies however relied on a mixture of primary and secondary data with varying degrees of reliability and detail. One key area of concern was greenhouse gas and energy accounting where 'Renewable Energy Credits' had been used to discount emissions (Vink, *et al*., 2007) or renewable energy sources had been used during production. Whilst this had been done perfectly openly and legitimately within the guidelines of LCA, if the results were taken out of context they could be misinterpreted, i.e. the benefit is wholly from the biopolymer rather than the use of renewable energy during its manufacture.

With the high profile of climate change during this time period, it was not surprising to find that half of the studies reviewed were focussed on quantifying the environmental impacts associated with energy consumption and greenhouse gas emissions. However the more comprehensive assessment studies identified other impact categories, such as eutrophication potential, as being of similar significance in terms of environmental impact of biopolymers, largely from feedstock production, and should not be ignored (Harding, *et al.*, 2007).

Finally, it was interesting to note that whilst a third of the studies identified could be directly linked to parties with a commercial interest in promoting the use of biopolymers, the majority of studies reviewed appeared to be impartial with academic interest only. Whilst this is a positive finding, it should also be noted that these independent studies were often devalued by the primary data made available to them.

5.3.1 *Summary and conclusions of LCA review.*

With the main interest towards the use of biopolymers in packaging applications stems from their perceived environmental benefits, it is clear that a much greater degree of certainty and consensus is required as to what these benefits are, and where and how they can be achieved. LCA, as an environmental assessment method, is currently one of the best tools available to achieve this, but it has its limitations. The quality of the findings from an LCA is very much dependent on the quality of the information input and the unbiased selection of the functional unit, scope and assessment methods. Also the results of an LCA often require a degree of expertise from the reader to interpret them correctly. The lack of clear consensus and guidance on the environmental impacts of biopolymers, supported by unbiased LCA is demonstrates that the current growth in biopolymer packaging applications is taking place without solid and uncontroversial scientific data in place to direct and underpin the decisions and choices that are obviously being made. There is a therefore a need for further and urgent LCA studies, particularly in the area of biopolymer applications and 'end of life' management to clarify their real environmental benefits and to identify the most suitable immediate applications for their use.

5.4 Sustainability – Addressing the Social dimension in LCA

The three pillars of sustainability, as defined at the 2005 World Summit on Social Development, require the reconciliation of economic, environmental and social needs. (United Nations General Assembly, 2005). Economic needs have always been a key consideration of most companies in competitive markets and many tools, methods and processes have been developed to support the effective economic management of those corporations and the design of cost competitive products (e.g. Cost Benefit Analysis, Company Accounting, Value Engineering and Lean Manufacturing). More recently environmental concerns have prompted the development of a number of new methods and tools, such as eco-design, Design for Environment (DfE) and LCA, to support manufacturers in reducing the environmental impacts of their products and processes.

Societal impacts however have focused mainly on corporate conduct and behaviour rather than individual products or processes. This approach is supported by the development of Corporate Social Responsibility (CSR) reporting within companies and advanced by academics such as Spillemaeckers *et al.* (2004) and Dreyer *et al*. (2006) who argue that most social impacts are caused by the actions or conduct of the company rather than its products or processes. However the necessity for manufacturing to be sustainable has prompted the need for tools and methods to support the sustainable design of products. Fundamentally, with the tools already available to manufacturers and designers on environmental and economic assessment, the key requirement would be to account for the social impacts of the company's product and processes (Schmidt, *et al.*, 2004)

A number of approaches have been suggested as to how social factors could be incorporated into existing processes and tools. One major area of interest has been the development of a social life cycle assessment (S-LCA) based on the same principles and methodology as a standard LCA used to conduct environmental assessment of a product or processes. Other approaches, whilst following the basic principles defined in ISO 14040, vary significantly in methodology. This diversity of approaches and lack of general consensus is indicative of the complexity and difficulty in attributing social impacts to a particular product or process – causal linkage. This current state of S-LCA is supported in a review by Jorgensen *et al*., (2008), entitled 'Methodologies for Social Life Cycle Assessment'.

5.5 Multi Criteria Decision Making in Complex Systems

One of the key challenges faced by practitioners, following the assessment of a complex system, is to make decisions based on multiple, sometimes conflicting, and often non comparable, criteria. Single attributes, such as cost, require very little in the way of decisions but when we consider 'value' which includes cost but also many other attributes such as quality, usefulness, robustness, etc. the decision making process becomes more complex. Sometimes these multi criteria can be translated into a single metric such as profit, carbon or joules, but in a complex system with multiple attributes, objectives and other variables, a single metric is unlikely to be particularly meaningful or useful. In LCA, it is sometimes necessary to simplify results when reporting to non-expert audiences such as government ministers or the general public. One metric for achieving this is the eco-indicator, which combines multiple environmental impacts into a single score, and is described as "being equivalent to one thousandth of the yearly environmental load of the average European inhabitant" (pre-consultants 2013).

However, the value of these types of metrics remains controversial and is prohibited by ISO14040, which emphasises openness and reproducibility of LCA results.

The complexity of decision making in packaging design is increased ten-fold by the addition of sustainability considerations. Already a complex process, as described in chapter 4, the addition of environmental and social criteria introduce new challenges that include both what to measure, how to measure it and how to compare results in a meaningful way that enable a balanced decision to be achieved. For example, deciding between a biopolymer and conventional polymer where one has higher GHG emissions but the other competes with food production, on what basis can these two options be compared, which allows a defendable decision to be reached as to which has the lowest overall impact. This issue with subjectivity in multi-criteria decision making is not unique to sustainable pack design. Belton and Stewart (2002) address this by suggesting that simply by formalising the decision making process and collating organising and evaluating all the available data in a structured and reproducible way, the decision maker can have confidence in the final outcome. However they warn that this approach does not guarantee a correct answer or ensure an objective analysis; rather that it simply allows subjectivity to be dealt with in a transparent manner.

As previously mentioned there are different types of multiple criteria and these can affect the complexity of the method adopted for supporting the decision making process. Described by Seppala *et al.,* (2002), as being either multi-attribute or multi-objective, the type of support required will depend on whether the options available to choose from are restricted or infinite. The selection of a biopolymer from a wide range of options would therefore require multi-attribute decision methods and these can be very simple or complex. Because of the complexities discussed in assessing biopolymer packaging on a range of sustainability criteria, it is likely that a more sophisticated method would be required such as an Analytical Hierarchy Process (AHP). These simple and complex methods are described by Wang *et al.,* (2009) and an example application of AHP in use is describe by Bayazit (2004).

5.6 Chapter Summary

With the realisation of the greater need for sustainability, particularly within the manufacturing sector, there has been a proliferation of research on how to assess and incorporate all three pillars of sustainability into the product/pack design process. This is particularly relevant to the use of biopolymers where the main objective is to improve the overall sustainability of the company’s packaging. This chapter began with an overview of the potential environmental and social impacts relevant to biopolymer packaging and was followed by a review of current research conducted on assessing the impacts of biopolymers using LCA. From this it has been concluded that the majority of LCA’s conducted to-date are over simplistic, inadequate in terms of scope, detail and range of impacts assessed and sometimes misleading in how the results are interpreted and presented. It is clear from the research reviewed in this chapter that a better understanding of the environmental impacts of biopolymer packaging compared to conventional polymer packaging is required and that further comprehensive, independent and unbiased LCAs would be the most likely means to achieving this although it is important to consider the likely future impacts as well as the current ones when evaluating the data.

A further requirement identified was the need to incorporate social factors into biopolymer ‘packaging’ assessment, particularly as the impact of diverting resources away from food production to biofuel and bioplastics has the potential to impact on the availability and affordability of commodity foodstuffs. Furthermore, combined with the use of land and water to grow non-food crops, these factors can have the greatest impact on the world’s poorest populations. From the conclusions made so far it is clear that a number of criteria need to be assessed if a full understanding of the impacts associated with biopolymer packaging are to be understood. Making decisions based on this wide range of different and sometimes incompatible or conflicting criteria can be problematic. A review of literature on research exploring how multi-criteria decisions can be made within complex systems identified a number of potential methods and algorithms which could be adapted for use within the sustainable design assessment and selection process. The next chapter will describe how the research methodology has been applied in this research.

Chapter 6 Research Methodology

6.1 Introduction

This chapter describes the research methodology used to undertake the research reported in this thesis, which follows the well-established, four stage approach widely adopted for research programs. The chapter begins with a brief description of these four stages of the methodology, supporting the approach taken for the research in this thesis. This is followed by a more detailed description of each of these four stages which include: a review of relevant literature together with the subsequent refinement of the research assertion; the development of a sustainable design framework for biopolymer packaging together with the associated assessment methodologies for an integrated sustainable and strategic approach; the development of a prototype sustainable design decision support tool and its associated case studies; and finally the analysis and discussion of results leading to the development of the research conclusions.

6.2 A brief overview of research methodology

Research is a structured inquiry that utilizes acceptable scientific methodology to solve problems and create new knowledge that is generally applicable (Grinnell, 1993). There are numerous definitions and classifications of research methods used in various academic disciplines such as engineering, social science, management, environmental science etc. One such approach classifies research from three perspectives (Figure 6-1): application of the research study; objectives in undertaking the research; inquiry mode employed (Kumar, 2005). Firstly from the perspective of application, research can be classified into two broad categories - pure and applied research; pure research can be quite abstract, whilst applied research focuses on solving practical problems (Kumar 2005). Secondly, from the perspective of its objectives, research can be broadly grouped into six key categories as shown in Figure 6.1.

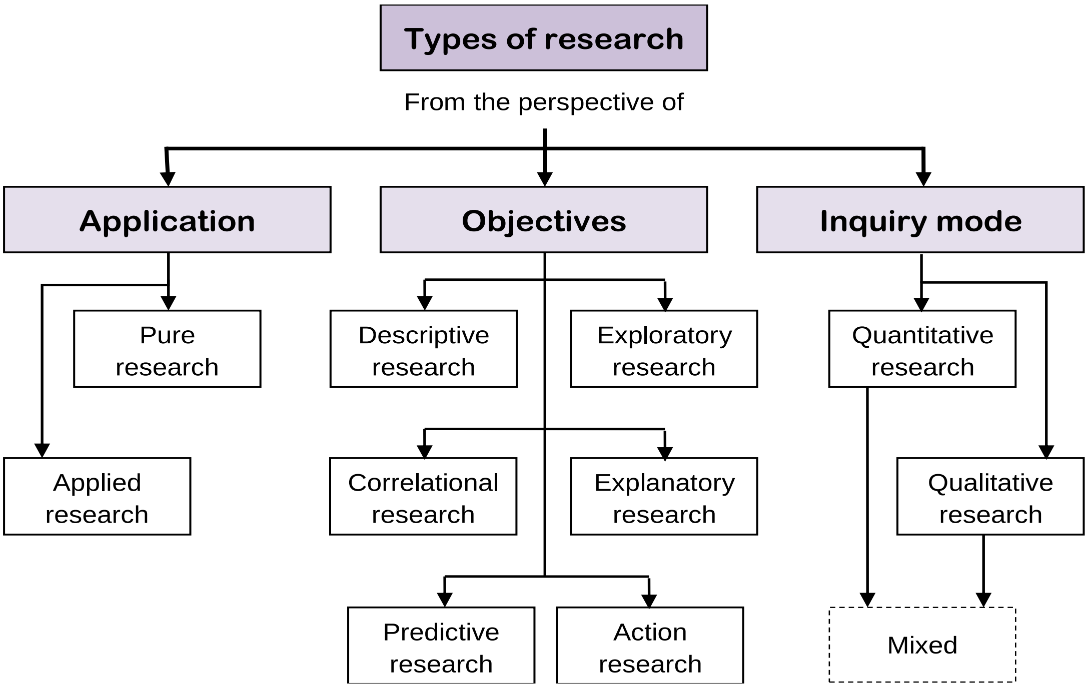


Figure 6-1: Types of research. Adapted from (Kumar, 2005)

- Descriptive research aims to describe what is prevalent regarding a particular situation, phenomenon etc.
- Exploratory research asks what happens and then tries to find out why.
- Correlational research attempts to ascertain if relationships exist between two phenomena.
- Explanatory research specifically attempts to explain why a relationship exists and how it is formed.
- Predictive research takes a number of variables and attempts to predict an outcome.
- Action research explores and informs practice (Kumar, 2005), (Whisker, 2001).

Finally from the perspective of inquiry, the process by which answers are found to the research question, there are commonly two classifications: quantitative or qualitative research (Cohen & Manion, 1994). A quantitative methodology generally involves the measurement of variables and the collection of statistically significant quantities of data. This is described as having a structured approach as the research follows a predetermined plan and is generally employed to measure the extent of a problem, issue or phenomenon.

A qualitative research methodology is more suitable for exploring the nature of a particular issue or phenomenon and is described as having an unstructured approach. This methodology allows a lot more flexibility in the research but is by nature more subjective. Both of these methodologies have advantages and disadvantages and can be mixed to suit the needs of a particular research project. The applied research adopted in this thesis follows a mixed inquiry mode and has explanatory and predictive objectives which are described in more detail in the following section 6.3.

6.3 Research Methodology

The four key stages of the research methodology adopted for this thesis are depicted in Figure 6.2 provided at the end of this chapter, as: Research assertion, aim, objectives and background; framework development and refinement; testing, validation and experimentation; and research discussions and conclusions. Within each stage the various key tasks are defined and ordered with the main connections and pathways between each displayed.

At the start of the first stage, the initial research assertion and hypothesis was established based on the prior knowledge acquired in this area during the authors career as a packaging management and design consultant. This involved a wide range of projects for many of the world’s leading brands and ‘blue chip’ manufacturing companies. This research assertion and hypothesis was then refined through further knowledge gained from a number of literature reviews of the relevant industrial and academic publications in this area. The final review of environmental design tools, methods and guides with application in the area of polymer packaging design had particular influence on both the refinement process and in directing the second stage of research of framework development and refinement.

The initial framework for the tool was developed from the knowledge and understanding gained during the first stage and the considerable experience of the author in this area. Further, unstructured discussions were had with industry contacts actively working in packaging design and where possible with experience of using bio-derived polymers, such that a more thorough and detailed consideration of the different industry, user and technical needs/requirements could be established. In addition to the guidance obtained from the review of existing eco-design tools, methods and guides, this review and subsequent assessment also provided clear support for the novelty of the proposed tool by identifying the existing gaps in knowledge. It was intended that the framework would initially be realized in a number of individual design modules which could be later brought together into a holistic eco-design decision support tool. In addition to the concepts of inclusivity and environmental assessment embodied in the initial framework, these were further developed to include integrated sustainability and strategic forecasting.

The third stage of the research involved the initial validation of each of the design modules using simulated and real world data. At this stage of the research, the scope of the tool was restricted to a single pack type and only those materials relevant to this pack were considered. The pack type was selected based on three case studies use the same pack format but for different companies. Within each case study different aspects of the tool were tested and outcomes recorded.

The final phase of the research methodology was to assess the research results from stage three and develop the concluding discussions and further areas of research needed.

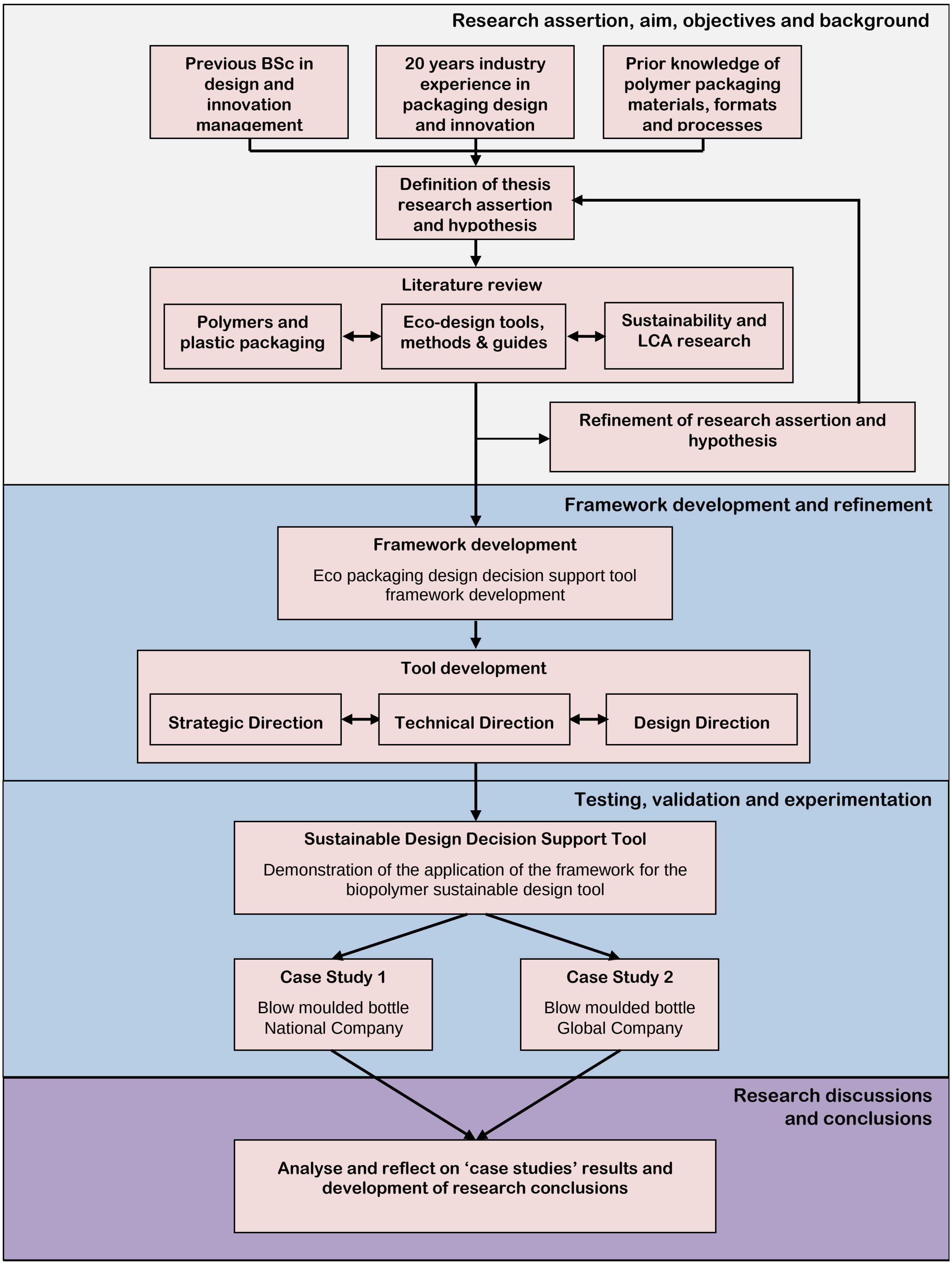


Figure 6.2: Research Methodology used within the Thesis

Chapter 7 An Integrated Framework for the Sustainable Design of Biopolymer Packaging Products

7.1 Introduction

This chapter presents a framework for the sustainable design of packaging products, with particular emphasis on the utilisation of biopolymers for commercial packaging applications, and forms the first of three research chapters describing the research activities undertaken in this thesis. This chapter begins with an outline of the three main areas of research focus and is followed, in section 7.3, with a description of the key differences between a conventional polymer pack design process and a biopolymer pack design process. Based on the results of this comparison between the two packaging design processes, an integrated framework for a sustainable packaging design is presented to support the appropriate use of biopolymers within commercial packaging applications. The chapter concludes with a description of the three design stages that form the basis of the sustainable packaging design framework.

7.2 Research Issues in Biopolymer Sustainable Packaging Design

While biopolymers are often promoted as environmentally friendly materials, their true environmental and social impacts are not so clear and are widely challenged. In particular concerns exist regarding their production and supply and how this might impact land use and the global availability and affordability of food. In addition to these ecological and social considerations, there are also the more established economic, technical and operational and aesthetic factors that must be understood regarding: material cost, scalability, security and consistency of supply, functional performance, impact on production and logistics, consumer acceptance and how they will be recovered or recycled at their End-of-Life. Based on these factors the following three main research areas are identified as the focus for investigation in this thesis.

1. To determine the key considerations and decisions necessary for the successful adoption of biopolymers for packaging applications. These are grouped into five categories: Strategic, Commercial, Technical, Operational and Design.

2. The linking and integration of these considerations and decisions within a sustainable design support framework for biopolymer packaging.

3. The development of a sustainable design support tool that facilitates the appropriate selection and application of biopolymers for use as packaging and its validation in a number of product case studies.

The first two of these research areas are discussed in more detail in sections 7.3 and 7.4 respectively of this chapter, while the third research area is described in chapter 8 and demonstrated through case studies in chapter 9.

7.3 Decision Support Requirements for Biopolymer Packaging Design

A primary objective of the research was the identification of the key considerations and decisions necessary for the successful adoption of biopolymers for packaging applications. Initially the traditional pack design process was investigated and, in total, five main steps were identified, plus one optional step where the development of a new material was required. This traditional pack design process is illustrated and described in subsection 7.3.1.

In the alternative sustainable pack design process, as proposed for biopolymers, three modifications to the traditional process have been proposed. Firstly, an additional step has been added at the beginning of the process, whilst previous steps two and three have been modified. This new process is illustrated and described in subsection 7.3.2. The two processes are then compared in subsection 7.3.3 and the key differences identified are used, in part, to demonstrate the need for the proposed eco-design support tool for biopolymer packaging.

7.3.1 *The traditional 'conventional polymer' packaging design process*

The processes discussed in this chapter are based on the design of primary packaging for consumer and retail markets. Primary packaging, usually in direct contact with the product, will be sold with the product and be disposed of by the consumer after use and includes items such as cans, bottles, bags, wraps etc. In addition to the design of a new packaging, the re-design and re-engineering of existing packs will also be relevant to this research, e.g. the direct substitution of an existing conventional polymer with a biopolymer where the original pack design remains otherwise largely unchanged.

The tasks involved in the conventional packaging design process have been grouped into 5 main stages: Preparation, Feasibility, Design, Development and Implementation. The preparation stage is a data gathering, sorting and communication exercise. The two key milestones in this stage are the initial preparation of a design brief and the subsequent development of a design specification. Next is the feasibility stage, which involves the identification of suitable materials, formats, and processes that meet the technical and commercial essential requirements for the design. If no material can be identified then either the design specification or brief needs to be modified, or in certain circumstances the company may develop a new material usually in partnership with a third party. This material Research and Development (R&D) stage is shown on the diagram as running in parallel to the feasibility stage, indicating that wider material search would continue during this development.

The design stage is where the pack concepts are created, evaluated and selected. This may involve a number of iterations from initial brainstorming of ideas, to visuals and finally 3-dimensional models or prototypes. Usually one concept is selected for the development stage, which will involve testing and trials. At the end of the development stage, the final specification for the pack will be produced, which will contain all the information required to manufacture that pack. The final stage is the implementation, which begins with approval of the pack across the business and continues with its market introduction and on-going monitoring of its performance.

An illustration of this traditional design process for conventional polymers is shown in Figure 7-1.

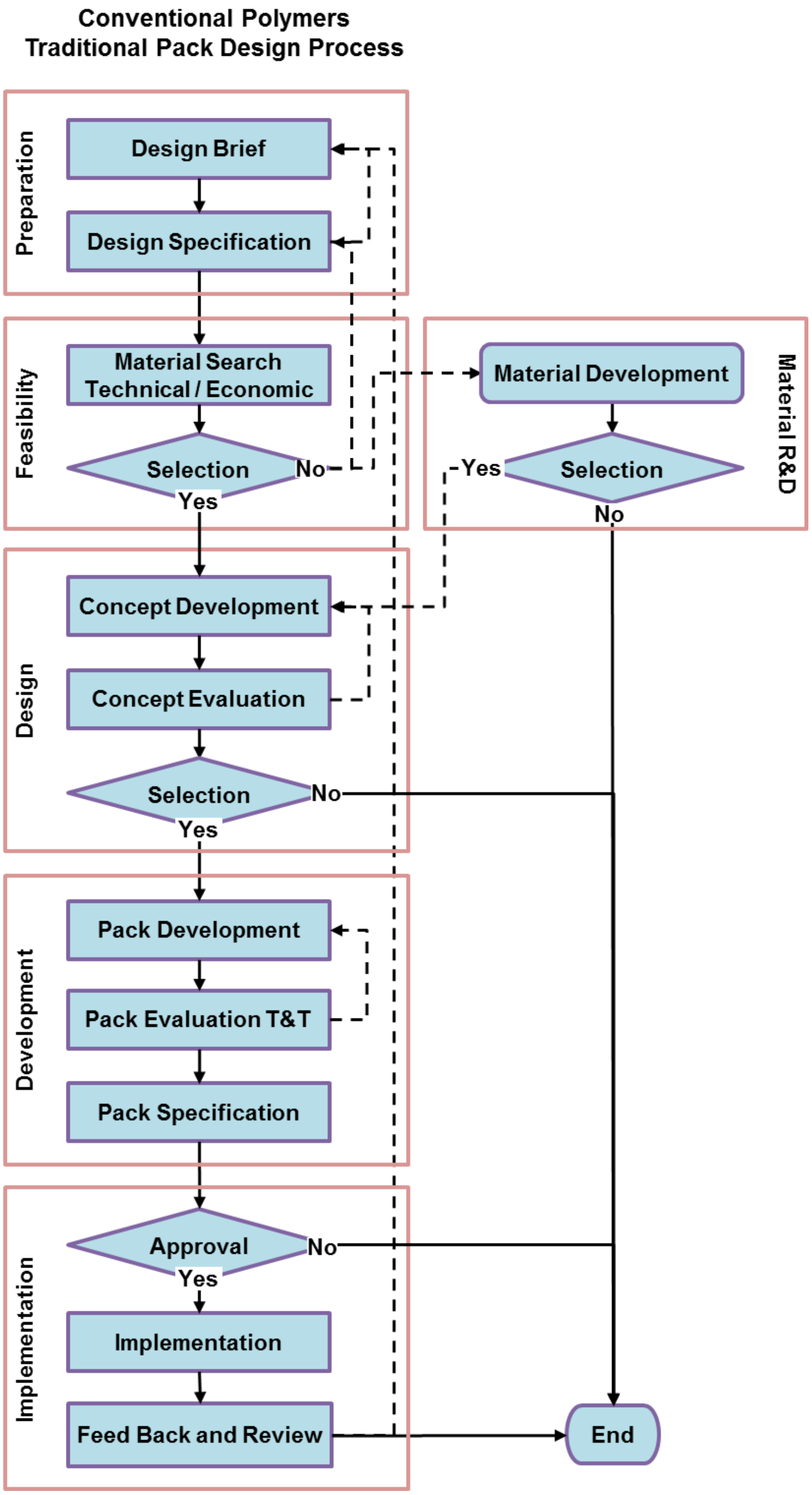


Figure 7-1: Key Stages in a Traditional Packaging Design Process using Conventional Polymers

7.3.2 *The Alternative Sustainable ‘Biopolymer’ Packaging Design Process*

The alternative sustainable design process for biopolymer packaging has six key stages: Strategy, Preparation, Feasibility, Design, Development and Implementation, as well as the optional Material R&D stage that runs in parallel with the feasibility stage. The alternative process begins with a Strategy stage, which is required at the start of the process, to ensure that the potential benefits achievable through the adoption of biopolymers are in line with the company’s strategic goals and expectations. In the traditional pack design process, the strategic goals are usually well understood by the business and might include reduced costs, increased margins/sales and greater profits. With the sustainable design process, the strategy driving the adoption of biopolymers is more complex involving social and environmental factors. Therefore, it is essential that before embarking on an expensive packaging development exercise and product launch, that the expectations are realistic and the strategic goals can be easily communicated and translated into design actions, which can be included in the design brief and design specification, produced during the Preparation stage.

The Feasibility and Design stages have been modified from the Traditional Design process through the inclusion of sustainability considerations, metrics and assessment criteria in the material database fields and in the concept assessment / selection criteria. It should also be noted that due to the immaturity of biopolymer development, companies are more likely to have an active role in the research and development of biopolymers than with conventional polymer materials.

An illustration of the proposed sustainable packaging design process for biopolymer packaging is shown in Figure 7-2.

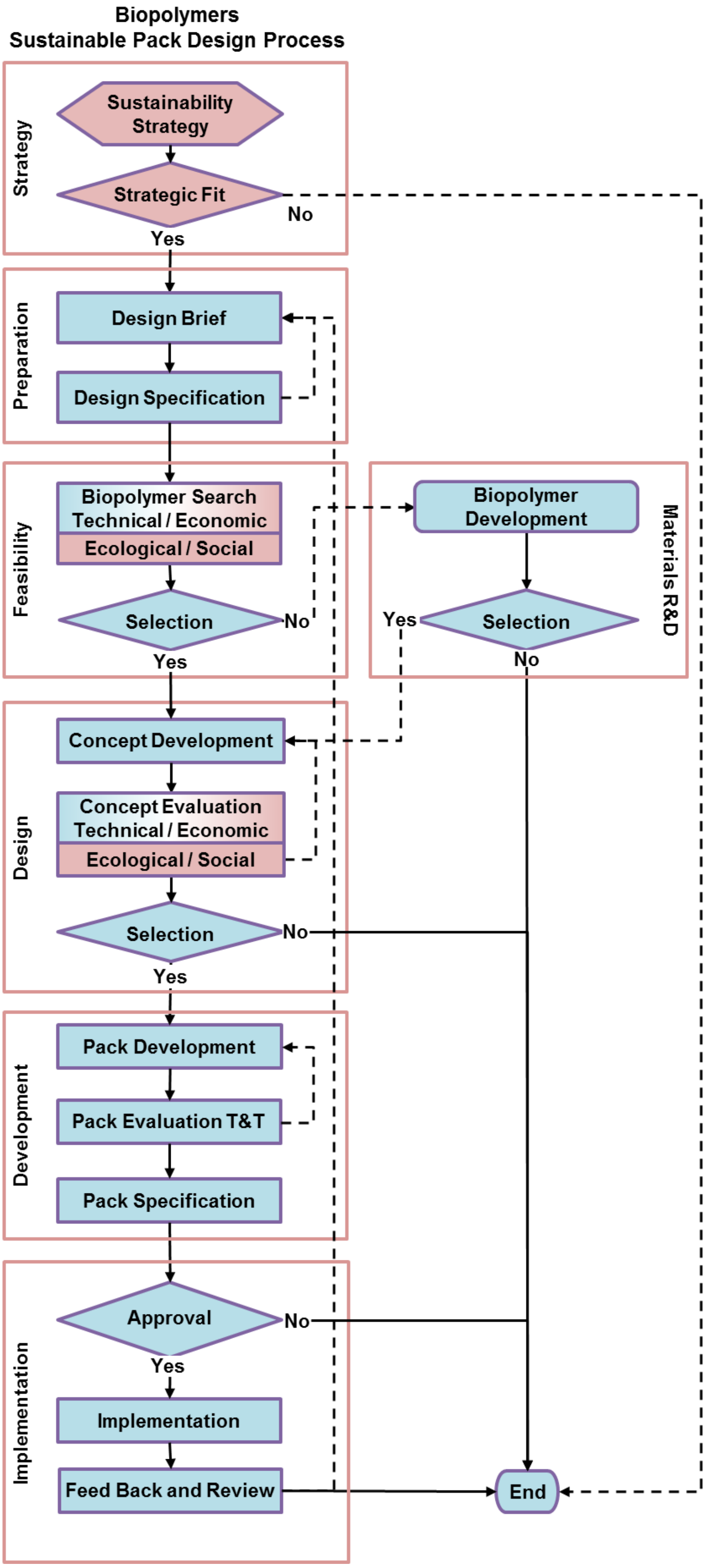


Figure 7-2: Key Stages in a Sustainable Packaging Design Process using Biopolymers

7.3.3 *Comparing the Two Processes*

By comparing these two process diagrams side by side, as in Figure 7-3, clear differences between the two processes become immediately apparent. The most obvious being the need for strategic decision support at the very start of the process.

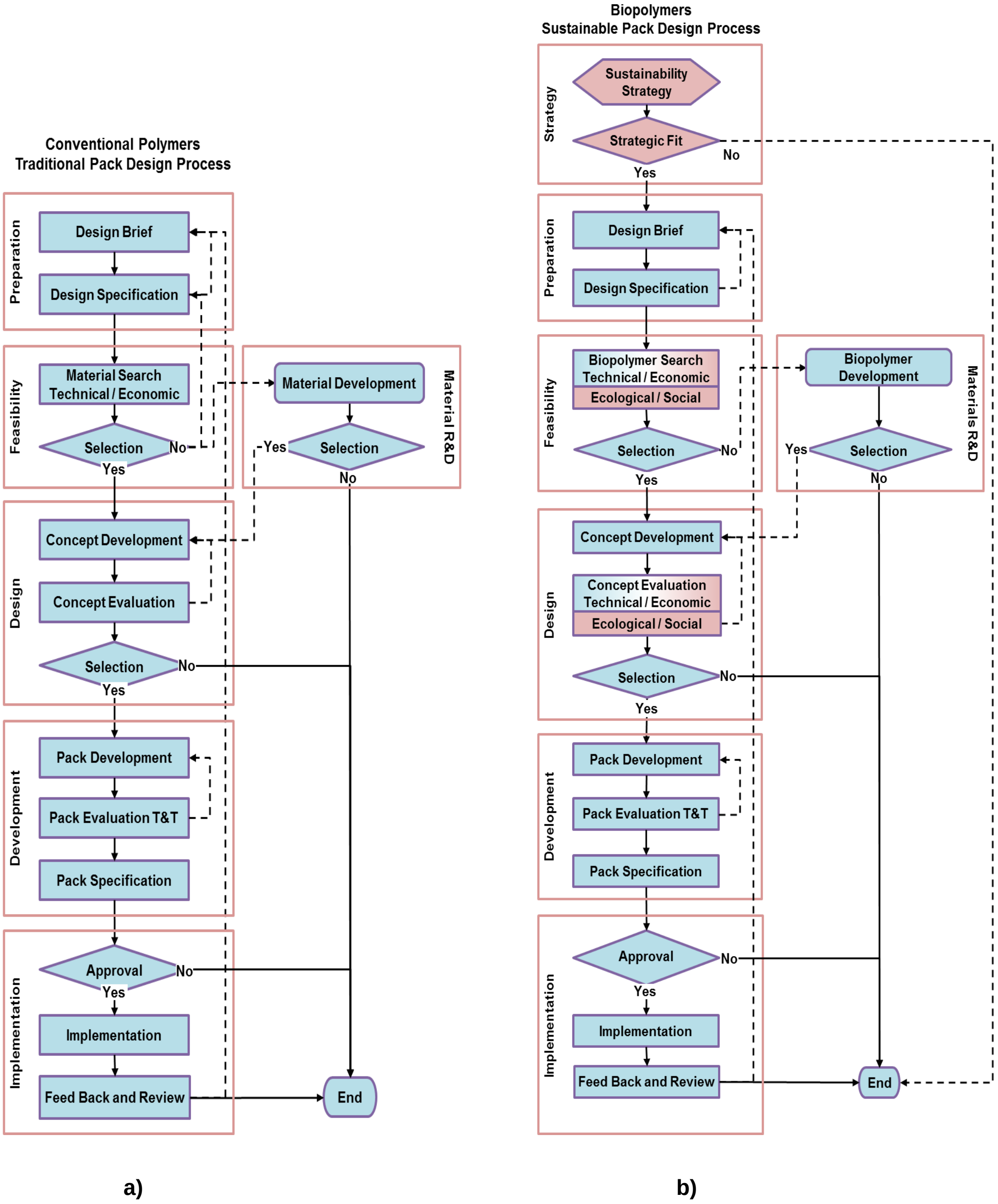


Figure 7-3: Comparison of figures 7.1 and 7.2 highlighting key differences.

a) Key Stages in a Traditional Packaging Design Process using Conventional Polymers

b) Key Stages in a Sustainable Packaging Design Process using Biopolymers

The key differences between these two processes are summarised in Table 7-1 and discussed in more detail in text below.

Firstly the question of, whether biopolymers can form part of a company's packaging strategy and contribute towards their overall business sustainability goals, needs to be addressed. These high level decisions, taken at director or by senior management, would primarily be concerned with the wider business implications of adopting biopolymer packaging. These strategic business goals, which include sustainability, must be accurately and simply communicated to the packaging design team. The traditional method of a design brief is used to achieve this but with additional 'sustainability' goals included. This design brief is then expanded into a design specification, which includes all the economic, technical, brand, product, manufacturing, logistics and sustainability requirements, prioritized as essential or desirable.

Table 7-1: Comparison of Key Process Stages between traditional and Sustainable Packaging Design (highlighted cells indicate a significant change in the process)

Process Stage	Sustainable Design for Biopolymers Packaging	Traditional Design for Conventional Polymer Packaging
Strategic	The decision to use biopolymer packaging is likely to be a strategic (sustainability) one. Biopolymers must contribute to achieving these strategic goals.	Not Required - Financial and technical strategic goals already communicated and well understood within the business.
Preparation	Essential and desirable design requirements identified and then specified.	Essential and desirable design requirements identified and then specified.
Feasibility	Identifies technical and commercial feasibility of design objectives, as well as sustainability goals	Identifies technical and commercial feasibility of design objectives.
Development	More likely	Less likely
Design	Uses sustainability criteria to direct design in addition to basic commercial and technical criteria.	Design decisions informed by basic commercial and technical criteria.
Development	Standard company testing and trialling procedures followed	Standard company testing and trialling procedures followed
Implementation	Standard company procedures followed.	Standard company procedures followed.

Producing a design specification requires consultation with personnel from each business area (horizontal: supply chain) that could be impacted by changes to the packaging at every stage of the packs lifecycle. This consultation would usually be carried out by middle management but would involve discussions with personnel from each section of the business hierarchy (vertical: operational, tactical and strategic). This is an iterative process, as in order to develop a realistically achievable design specification changes may be required to the original brief.

A material search would then be conducted for any commercially available biopolymer materials that meet the essential and as many of the desirable requirements of the specification. Once all the potentially suitable materials have been identified, an initial selection process based on the most promising and potentially beneficial biopolymers would be made. If no suitable material can be found, then material research and development can be explored. If successful the material(s) would then be available for use in the concept development.

The development of packaging concepts is largely the same for both processes, although the designer may require technical support regarding the properties of the biopolymer. However the assessment of the pack concepts will require the assessment of environmental and social impacts in addition to the more traditional criteria, such as economic, technical and aesthetics performance. As with any evaluation of this type, the whole life cycle for each pack concept needs to be considered. The concept evaluation can be an iterative process, informing the design process, as well as being used for concept selection.

The remaining stages, for both processes, involve the development, testing, trialling and implementation of the final pack design. The key difference being the additional data on sustainability measures in the alternative process that would be included in any subsequent evaluation and approval.

A bespoke and novel framework has been investigated for a holistic and integrated approach to the sustainable design of biopolymer packaging based on the key additional requirements identified in this section. This framework is presented in the following section 7.4.

7.4 Sustainable Design Framework for Biopolymer Packaging

The Sustainable Packaging Design Framework (SPDF) for biopolymers, as proposed in this thesis, is solely concerned with biopolymers in packaging applications. Whilst many factors are considered during the specification, selection and design of a pack, this framework is concerned only with those factors specific to the comparative analysis of biopolymers. It should also be noted that the framework is intended to support, and not to replace the existing pack design process.

To achieve this goal a systematic approach is proposed to review, select and assess the use of biopolymer packaging in terms of its potential for reducing the environmental, social and economic impacts of conventional polymer packaging. The SPDF for Biopolymers consists of the following three stages as shown in Figure 7-4.

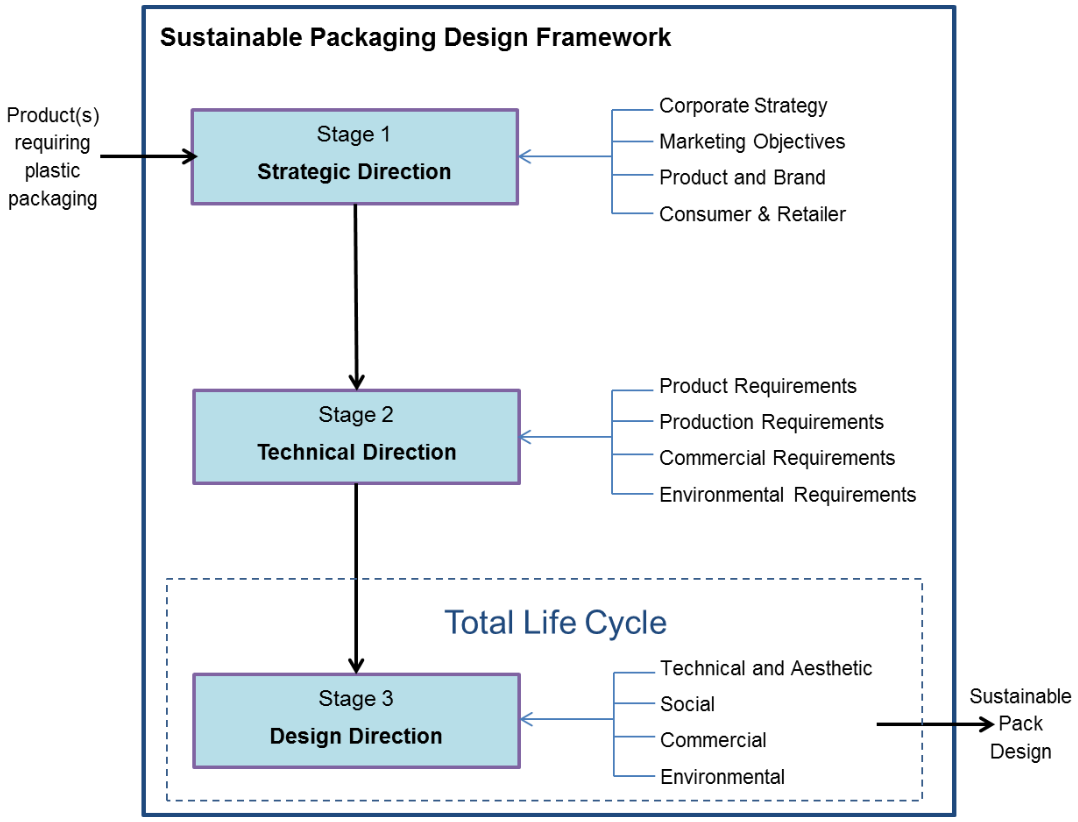


Figure 7-4: The Sustainable Packaging Design Framework (SPDF) for Biopolymers.

The first stage aims to highlight the potential for biopolymers to contribute to the achievement of the company's business, corporate social responsibility (CSR), and/or packaging strategies. The output from this first stage is the translation of the strategic goals into a set of actions, which will aid the development of technical, commercial, social and environmental requirements specifications. These specifications will be used in the second stage to evaluate and select the most appropriate biopolymer for the required application. In the third stage, a life cycle approach will be used to assess and systemically identify the potential benefits of the selected biopolymer pack concept.

The framework should enable the environmental, social and economic impacts to be assessed across the packs whole life cycle and provide a mechanism to allow the final results to be compared against the original specification and strategic objectives. The complexities involved in integrating this sustainable thinking into the current pack design process are primarily two-fold. Firstly there is the challenge of combining the three key 'pillars' of sustainability into a single assessment score and secondly, there is the difficulty in integrating these sustainable design considerations and activities into the existing pack design processes and requirements. The key tasks involved in each stage of the SPDF are described in more detail in the remaining sections of this chapter. Figure 7-5 illustrates the steps in stage one of the SPDF.

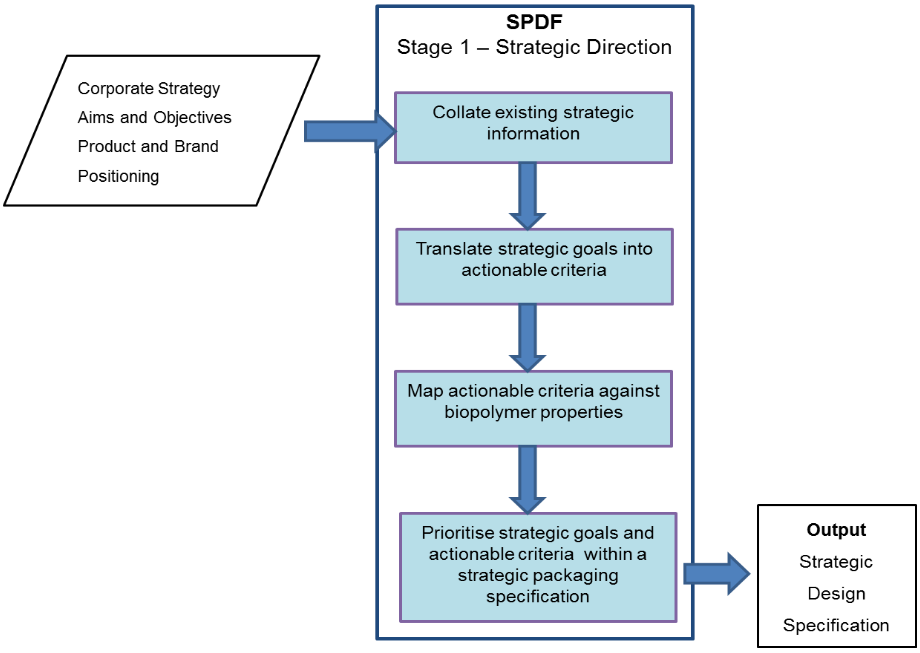


Figure 7-5: Key tasks in stage one of the SPDF

7.4.1 *Stage 1: Strategic Evaluation*

The aim of the strategic review is to establish the potential for biopolymer packaging to contribute to the relevant strategic goals of the business and if appropriate, support the translation and communication of these strategic goals into business actions. Traditionally strategic goals have been relatively easy to communicate in financial terms to the rest of the business. However, when trying to communicate less traditional strategic objectives such as sustainability, responsibility, and knowledge etc., as would be the case with biopolymers, the traditional financial model proves inadequate. Studies carried out by Professor Robert S. Kaplan and David P. Norton in the early 1990's concluded that increasingly, long term strategic objectives were becoming more difficult to translate into simple financial measures and targets (Kaplan and Norton 1996). These findings led them to develop the Balanced Score-Card (BSC), which was later adapted to include sustainable measures, becoming the Sustainability Balanced Score-Card (SBSC). As discussed later in this chapter, there are problems associated with implementing an SBSC, which in the case of biopolymers, would primarily be lack of existing knowledge and senior management time. The strategic review stage aims to address these issues by eliminating the need for specialist knowledge and to minimize the amount of time required to get to an actionable result. This is achieved through the following three tasks

a) Definition of current business sustainability strategy
b) Mapping of key strategies against biopolymer properties
c) Prioritisation and communication of strategic goals

The strategic review begins with the definition of the existing business sustainability strategy according to the three 'pillars' of sustainability – Economic, Environmental and Social. The information gathered at this stage could vary from a vague corporate mission statement to a clear set of strategic aims and objectives.

This second task involves mapping the key strategic sustainability and business objectives against the biopolymer properties and impacts of packaging. These would be grouped to include economic, environmental and social factors, as well as technical and commercial requirements. The outcomes from this stage will be threefold; firstly an answer to the general question as to whether or not biopolymers can contribute towards the company's strategic goals on sustainability. Secondly an understanding of how the use of biopolymers would support the product and brand and thirdly an understanding of the specific biopolymer properties that would contribute to attaining each strategic goal.

Having identified the key strategic goals, the next step is to prioritise and then communicate them, based on their level of importance to the business. This would then be included into a top level 'design brief'. The design brief will outline the key objectives and strategic goals of the business that are expected to be met in full or part through biopolymer adoption as well as the technical and commercial requirements that must be met.

7.4.2 *Stage 2: Material Selection*

As biopolymers are still in the early stages of their development, identifying the right grade of material for a particular application can be problematic. In addition to the degradable biopolymers such as PLA, TPS, RC etc., there are numerous grades based on the processing method and modifiers added. Whilst information may be available for some of these materials, others are difficult to assess because their exact formulation is kept secret. Having established that the adoption of biopolymers warrants further investigation, the next stage in this process is to identify which biopolymers from which suppliers should be investigated further. To achieve this it will be necessary to identify what information is required for a material to enable this selection process to be efficient, e.g. technical and commercial information as well as social and environmental. This database will then need to be populated with information on currently available biopolymers and maintained. Finally an interface will be required to allow the user to interrogate the database and for the information to be returned in a usable and manageable way.

The requirements for tier two have been based primarily on the need of a user to identify suitable materials that meet the criteria they have set and to identify the most appropriate supplier of these materials. The criteria would include all the technical performance data on the material such strength, barrier, melt etc. as well as processing information such as machine settings, shrinkage, handling etc.

Other information held within this tool would be the commercial, environmental and social performance of the tool. Whilst it is not expected that the tool will be able to hold every detail of a material covering all possible aspects of its performance, it should contain sufficient number of the most essential from each area to allow material selection to be made to the point of short listing but not necessarily to final specification.

As can be seen from figure 7.3 it is anticipated that whilst the majority of users will be from the middle management / skill level, the tool should be accessible to a range of users with varying levels of technical knowledge and provide a range of outputs from simple lists to detailed data sheet. The key requirements include:

- User Interface: Adaptable to technical ability
- User Inputs: Menu selection or user entered
- Time Requirement: Varied according to detail – 1 to 20 minutes.
- Output: Simple list to detailed data sheet
- Flexible: Applicable across a wide range of industries
- Tactical: Performance and processing data
- Sustainability: Considers Environmental, Social and Economic factors
- Strategic: Future as well as current performance

Various options have been identified which could support the stage two framework including spread-sheets and databases. Examples of tools based on these software platforms can be found in the tool review chapter 4. The following section provides a brief description of the different potential software options that are available and identifies the strengths and weakness of each in meeting the requirements for this stage, as outlined previously in this section.

Text Documents: Text rich formatted documents and tables are useful for recording large amounts of written information but are less useful when searching data or manipulation of information is required.

Strengths of using text documents for this application:

- Simple to use and customize.
- Document can be searched by key words.
- Software generally widely used and available to most users.
- Easy to output data sheet.
- Can hold wide range of information.

Weaknesses of using text documents for this application:

- Data held as text, so is difficult to search multiple documents and set different search parameters.
- Offers limited manipulation of numerical data and so restricts forecasting and complex parameter based searches.

Spreadsheets: These widely available software programs such as Microsoft Excel can perform quite complex data manipulation tasks and are widely used in business for simple calculations and costing purposes, producing graphs and charts and for creating searchable lists. Spreadsheets are generally two dimensional, such that the information is contained either in lists or columns and so differ from databases which are three dimensional having relationships between fields. (Note, a third dimension can be created in excel using layered spreadsheets)

Strengths of using spreadsheets for this application:

- Simple to use spreadsheets can be pre-programmed to manipulate text and numeric data using pre-defined interfaces and controls.
- Input can be prompted and results returned quickly.
- All different fields can be incorporated to cover requirements.
- Easy to modify and change as development progresses.

Weaknesses of using spreadsheets for this application:

- As the size and complexity of the data grows, so the interrelations between fields become more difficult to manage.

Databases: There are a number of database options from ‘off the shelf’ packages such as Microsoft’s Access, to individually designed and programmed databases. Alternatively it may be possible to use an existing ‘engineering materials’ database such as Granta Design’s ‘CES Eco-Selector’ and modify it as required.

Strengths of using databases for this application:

- Can be designed with different interfaces to match user skills and requirements including allocating different access to different groups so allowing new information to be added by skilled users.
- Capable of storing, sorting and searching large amounts of data at high speed.

Weaknesses of using databases for this application:

- Once a database has been design and constructed with the various relationships between fields etc. specified, it becomes difficult to make major modifications.

7.4.3 *Stage 3: Sustainability Assessment*

This third stage of the framework will support the comparative analysis of either biopolymer materials or pack concepts made from biopolymer materials. It is intended that a range of criteria will be included, such as technical performance, energy use, emissions, resource use, social impact etc., and that either full or part life cycle assessment can be made. This support can be used by the designer during the multiple design iterations that take place within the creative process, as well as in the key decision points or gates, which may involve a number of decision makers from across the business. The intention of this stage is to support the existing pack design decision process, not to replace it. As such the focus of this framework will be on evaluating the sustainability aspects of the polymers and those key technical and operational differences relevant to biopolymer packaging evaluation and assessment. Subjective decisions, such as aesthetics and consumer preference, will still have to be assessed using existing methods. Each of the three key pillars of sustainability will be considered in relation to biopolymer packaging.

7.4.3.1 Environmental Issues

Biopolymers are particularly complex to assess as they are currently produced from a wide range of feedstock (e.g. sugar cane, wheat, sugar beet, corn, cellulose). Each of these crops have many varieties, which are grown in different climates and soil types, using wide ranging farming methods. This makes it difficult to attribute a single global average value for production as is often used with conventional polymer production. Also whilst many end-of-life management options exist for biopolymers such as composting, incineration, gasification, anaerobic digestion, mechanical and chemical recycling, in many countries the infrastructures to facilitate these are limited or non-existent. So, in the short term, the majority of biopolymer packaging waste will still go to landfill, but in the long term this could be improved.

Thus even a balanced and comprehensive LCA will only provide guidance on current environmental impacts, understanding how this will change in the future is as important to companies when making strategic, long term investments. For instance whilst the negative impacts associated with biopolymers are reducing with advances in crop science and processing technology, the negative impacts associated with fossil fuel production are increasing as lower quality and higher polluting reserves are exploited, e.g. Canada Oil Sands, Brown Coal, Shale Gas (Bergerson and Keith 2006; Howarth *et al*. 2011).

7.4.3.2 Social Issues

Social, like environment, comprises of multiple impacts. Ensuring only the most relevant impacts are included within the Social Life Cycle Assessment scope is vital in balancing effort and accuracy. Assessing social Life Cycle impacts remains a major challenge and although a number of alternative approaches have been proposed (Dreyer et al., 2006; Spillemaeckers et al., 2004; Schmidt et al., 2004) there is as yet no clear consensus on which method or approach should be used, what impacts should be included and how they should be measured, assessed and reported (Jorgenson et al., 2008). For comparing biopolymer with conventional polymer packaging three key social impact categories have been identified. The first of these is Wealth and includes three sub categories of Home, Land and Livelihood. The second is Health, covering three groups: Workers, Consumers and Community. The third category is Well-being, and again is subdivided into three groups covering: supply, safety and stability.

A particular area of social concern is the impact of biopolymers on food availability and affordability. Concerns have been raised regarding our ability to meet the world's future nutritional needs, particularly with predicted increases in world population, consumption and the rising demand for renewable materials from industry (e.g. bio-fuels, energy, and materials). In this case it is suggested that the production of biopolymers would be unsustainable and already some companies are vehemently opposed to the use of biopolymers derived from food crops.

It is worth noting however that in 2011 the global production of biopolymer was 1 million tonnes, less than 1% of the total global plastics production and would have used less than 0.1% of the total food produced for human consumption. In fact less than 1% of the world's 'Human' food production would be needed to produce the global annual plastics consumption in biopolymer equivalents. This is significantly less than the 1.3 billion tonnes of food (33%) that is wasted each year (SIK, 2011).

7.4.3.3 Other Issues

Furthermore the packaging eco-design process where only biopolymers and conventional polymers are considered differs to the conventional pack design process where a variety of pack formats, materials and process are considered (Figure 7-2). The first key difference is the much broader scope of conventional pack design in terms of pack types and materials used. For instance, in designing a new beverage pack, a range of potential formats might be considered; PET Bottles, aluminium cans, glass bottles, aseptic pouches and cartons, all of which vary significantly in terms of their Commercial, Technical and Operational impacts on the business.

Biopolymer pack design however would place a greater emphasis on the environmental, social and economic impacts once an operational and technical match has been identified. As a result of this, the justification in the conventional pack would be based on measurable, quantitative data, whilst the biopolymer pack would rely more heavily on subjective and qualitative data in its assessment. Other differences include the most significant impact stages in the life cycle and which level in the business would be the main driver of change. For biopolymers, the drivers for change would be predominantly strategic whilst for conventional packaging these would be largely tactical and operational.

Table 7.2: Comparison of conventional pack design

	Conventional Polymer Pack Design	**Biopolymer Sustainable Packaging Design**
Scope: Materials	Compared against: Glass, Paper, Metals, Ceramics etc.	Compared against: Conventional Polymers
Key impacts considered	Commercial, Technical and Aesthetic	Environmental, Social and Economic
Justification	Measurable and Quantitative	Qualitative and Subjective
Key Life Cycle Stage Impacts	Production, Conversion and Use	Raw Materials and End-of-Life
Driver Level	Tactical and Operational	Strategic

It is therefore essential that a holistic approach is taken during the packaging design process, when considering the use of biopolymers, to ensure that the final packaging meets the original intent and overall requirements of the business. The framework to support this holistic approach will need to include inputs from a diverse range of stakeholders both within the manufacturing organization and externally; from across the supply chain.

Current eco-packaging design decision support tools are generally restricted in use to specialists within the pack design process, such as structural designers or packaging engineers, and provide largely tactical rather than strategic support and guidance. This disconnect between the inclusivity of stakeholders and strategic support required for a holistic design approach and the exclusivity and largely tactical support given by current eco-design decision support tools indicates a clear need for a new decision support tool for sustainable pack design using biopolymers.

Finally, with over 1200 grades of biopolymers available for commercial use in packaging, and many more in development, the ability to match the strategic, technical product and operational requirements of the business with the most appropriate biopolymer is essential. The framework should facilitate the practical aspects of biopolymer eco packaging design as well as the theoretical ones.

The above discussion highlights the need for a holistic, integrated and systematic approach to the use of biopolymers in eco-packaging design projects to reduce the overall environmental impact of plastics packaging and the use of fossil fuels.

These are described in the following sections and consist of three key stages as follows:

- Rapidly assess the potential benefits of using biopolymer packaging within their business to meet their strategic goals.
- Identify the most appropriate materials available that meet the strategic, tactical and operational requirements.
- Provide comparative assessment between different pack concept options using biopolymers and conventional polymers

The requirements for the Stage 3 framework have been based primarily on the needs of medium to highly skilled users such as designers, technologists, packaging managers and environmental analysts. This is primarily due to the level of technical detail, quantity of information and the time required to conduct a pack assessment or comparison. Therefore whilst the information produced from the use of this tool may inform the strategic plans of the business, it will be most useful during the realization stages of development and implementation.

The requirements for the third part of the tool framework, Stage 3 are outlined as follows:

• User Interface:	Clear, structured and detailed
• User Inputs:	Flexible and adaptable
• Time Requirement:	Hours to days depending on level of complexity
• Output:	Graphic and tabulated. Adaptable and Comparative
• Flexible	Applicable across a wide range of industries
• Sustainability	Considers Environmental, Social and Economic factors
• Integrated	Provides a means to weight and compare different
• Strategic	Future as well as current impact considerations

The Stage 3 framework is the most complex of all the stages, as it must deal with a wide range of variables in terms of information input and outputs and the calculation and manipulation of that data. There are a number of existing tools that can perform life cycle assessment such as Gabi and SimaPro as well as packaging assessment tools such as the Packaging Impact Quick Evaluation Tool (PIQET) and the Comparative Packaging Assessment tool (COMPASS), however these are limited mainly to environmental impacts. To provide an integrated approach the framework not only has to accommodate social and economic impacts in addition to environmental ones but also enable comparisons between them to be made. So for instance if one pack uses more water whilst another produces more CO_2 or one creates 5 jobs whilst another improves the quality of life for 10 people by 19%, how can the relative merits of each be compared, such that a choice can be made between them. Furthermore, the future impacts of different materials need to be considered, particularly when investments in production, handling, waste treatment etc. have to be made.

Due to the complex nature of this part of the tool it is likely that only a bespoke designed and coded software package could provide the necessary flexibility and range of features in one package. However, individual processes and features, such as the projection of future impacts, can be developed and proven in principle using simple formulae on paper or in spreadsheets before incorporating into a software tool. It is therefore anticipated that the initial Tier 3 prototypes will be constructed using variety of different programs and mediums.

7.5 Chapter Summary

This chapter has outlined the sustainable biopolymer packaging design framework along with its three stages, namely the strategic review, material selection, and detailed assessment. The problems facing manufacturers when considering the use of biopolymers for the packaging of their goods are addressed in each of the three stages. The Sustainable Packaging Design Framework described in this chapter has also been presented at the CIRP conference and BEPS conference both held in 2011 and also published in the Journal of Polymers and the Environment. Copies of these papers are provided in the Appendix (A2 and A3).

The framework advances previous research on sustainable packaging design by considering the key strategic goals of the company and including social as well as environmental, economic requirements and providing a mechanism for considering these alongside the other design criteria such as technical and emotional requirements through a holistic approach. In order to support the application of this framework within the manufacturing industry, this research has generated a computer aided design support tool, which aids each of the stages of the sustainable packaging design framework. The design and implementation of this prototype system is described in Chapter 8.

Chapter 8 The CASPPa Design Support Tool

8.1 Introduction

The previous chapter provides an overview of the Sustainable Packaging Design Framework. This chapter describes the design and implementation of a Computer Aided Sustainable Plastics Packaging (CASPPa) design support tool that has been developed to support the application of the SPDF within brand owners and packaged goods manufacturers. The main purpose of the tool is to support the use of biopolymers as part of a sustainable packaging strategy and to ensure the effective communication of this strategy, through the pack development process, such that the original strategic intent is not lost. At various stages of design, such as concept and pack selection, the tool supports a number of ‘what-if’ scenarios for the use of alternative biopolymers to assist in the selection of the most appropriate material from which to construct the pack. In addition to biopolymers, the flexibility offered by the tool would, once populated, enable a wide range of other packaging materials (plastics, glass, paper and board) to be incorporated into the tool. This chapter begins with a general introduction to the tool and then considers each tool Tier using an example to illustrate the functionality processes employed. Two case studies are provided in Chapter 9 to demonstrate the use of the tool and in particular the importance of the strategic direction on the final outcome of the pack design.

8.2 A Computer Aided Three Tier Approach

The research assertion within this thesis proposes that a company’s decision to adopt biopolymer packaging for its product(s) is based primarily on meeting strategic goals that extend beyond the traditional financial ones of lower cost or improved performance. It is therefore essential that the suitability of biopolymers to deliver these alternative strategic goals is confirmed to a specified degree of certainty before the company expends valuable resources in pursuing a direction that is fundamentally flawed. To achieve this it is proposed that two fundamental questions must be answered: What are these actionable strategic goals that seek to be realised by the use of biopolymers, and to what degree might biopolymers be able to achieve these strategic goals? In the first instance, this will involve translating the broad corporate level strategy into specific actionable goals relevant to the use of biopolymers, which can then be clearly communicated and understood at an operational level. Secondly, to quickly assess the potential of biopolymers to meet these goals will require the appropriate detail of biopolymers data to be held, particularly where there are no absolutes but degrees of probability. This is particularly applicable to biopolymers, which are still in their infancy and are often developed on a bespoke basis for a particular application; just because it is currently not commercially available does not mean that it can't be produced. Also, it is also important when considering the use of a material based on achieving sustainable or environmental improvements that the impact of these materials are considered over the whole lifecycle of the product. These impacts can vary considerably between different applications and so only a full life cycle assessment of the final pack/product by the company can determine its absolute performance. In the early stages of the design process this is not possible due to the constraints of time and clarity, and direction can often only be realistically provided in terms of the potential and risk, rather than specific directions.

The packaging design process is also very complex and made even more so by the need to consider and balance the additional sustainable criteria (social and environmental), with the traditional, diverse and sometimes conflicting considerations of aesthetics, technical, commercial, and operational requirements. The creation of a pack that meets the requirements of the manufacturer, product, brand, markets, retailers, consumers and recyclers, whilst optimizing the balance between environmental, social and economic needs, can only be achieved effectively through inclusion of multidisciplinary actors from across the supply chain during the design process. Many companies have developed comprehensive systems and processes to do this, however from the tool review it is apparent that these do not directly support the inclusion of original strategic intent, which even if present at the start of the process can easily be corrupted or forgotten and so lost from the final pack design. It is therefore a key objective of the CASPPa design support tool to ensure that the original design intent is retained and considered at each key stage of the design process, in addition to supporting the other sustainable pack design activities.

To support the development and implementation of the SPDF for biopolymers, an initial tool was developed, referred to as an Integrated, Sustainable, Inclusive and Strategic (ISIS), eco-packaging design tool, which aimed to aid the sustainable packaging design process through computer based tool and to provide support on the use of biopolymers at each key stage of the design process. An illustration of the initial design for the implementation of this ISIS eco-design tool is shown in Figure 8-1, which shows activities undertaken by the tool at each stage of the design process.

During the initial period of tool development the work focus was directed at the latter stages of the design process in Tier 3, on how to assess the performance of a pack on a range of criteria that are: difficult to measure i.e. social; and complicated to assess, i.e. environmental. Also, having assessed these criteria, how can decisions be made from multiple criteria that are not directly comparable. However it became clear during the latter tool development and testing stages (including trials with the London design consultancy, TPG International) that the support provided by the tool in the latter stages of the pack design process had been largely supplanted by the recently released commercial pack design software such as (PIQET, COMPASS and CES) and from advances in the abilities and skills of packaging designers to use LCA and standard foot-printing methods to incorporate sustainability into the in-house design processes.

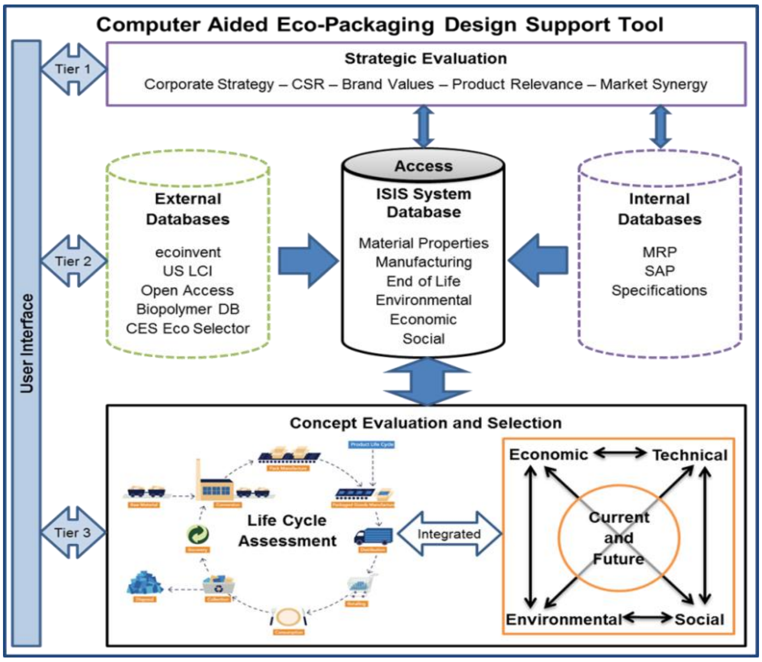


Figure 8-1: An overview of the original implementation of the ISIS Eco-Design Tool

The original assertion of the need for support in the early stages of translating and communicating the strategic goals and maintaining the strategic intent throughout the design process held true. Having established that it was the early stages of design support, at the strategic level, where there was the greatest need for support and where little focus had been given by current research or sustainable packaging design tools, the development focus shifted to Tier 1.

The original ISIS tool was redesigned to focus the provision of design support on the initial ‘strategic’ stages (Tier 1) and to ensure that the outcomes from this were incorporated into the remaining design stages (Tiers 2 & 3). Steps within the tiers that duplicated ones already available from existing processes and tools were scrapped, simplifying and streamlining the steps within each tier.

The new tool, named CASPPa, was constructed using a combination of existing software programs, including Microsoft Word, Excel, Access and Visual Basic, as most appropriate and the overview of the CASPPa Eco-Design Tool is provided in Figure 8.2.

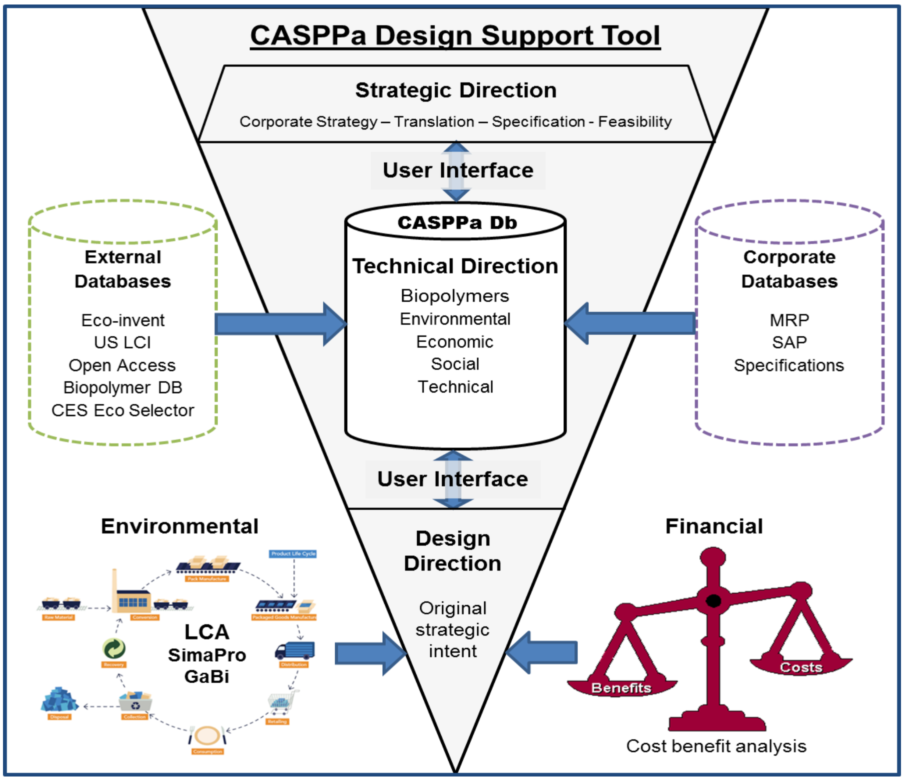


Figure 8-2: An overview of the CASPPa Design Support Tool

The focus of the CASPPa tool on the beginning of the process, compared to the original direction of ISIS and the approach taken by other eco-design tools is illustrated in Figure 8-3. This clearly shows that the focus of the new CASPPa design support tool is on supporting the early stages of the design process (Tier 1), in comparison to the original ISIS tool that focused more on the latter stages of concept selection (Tier 3).

The tool also aims to support the SPDF processes through the use of three progressive Tiers that provide direction at each key stage of the design process ensuring that the original purpose (strategic intent) is not lost in the complexity and duration of the design process.

Each Tier has been developed mindful of the intended user(s) needs and limitations. Considerations such as knowledge, skills, resources and process complexity have influenced the design and implementation of each tier of the tool as exemplified in figure 8.4.

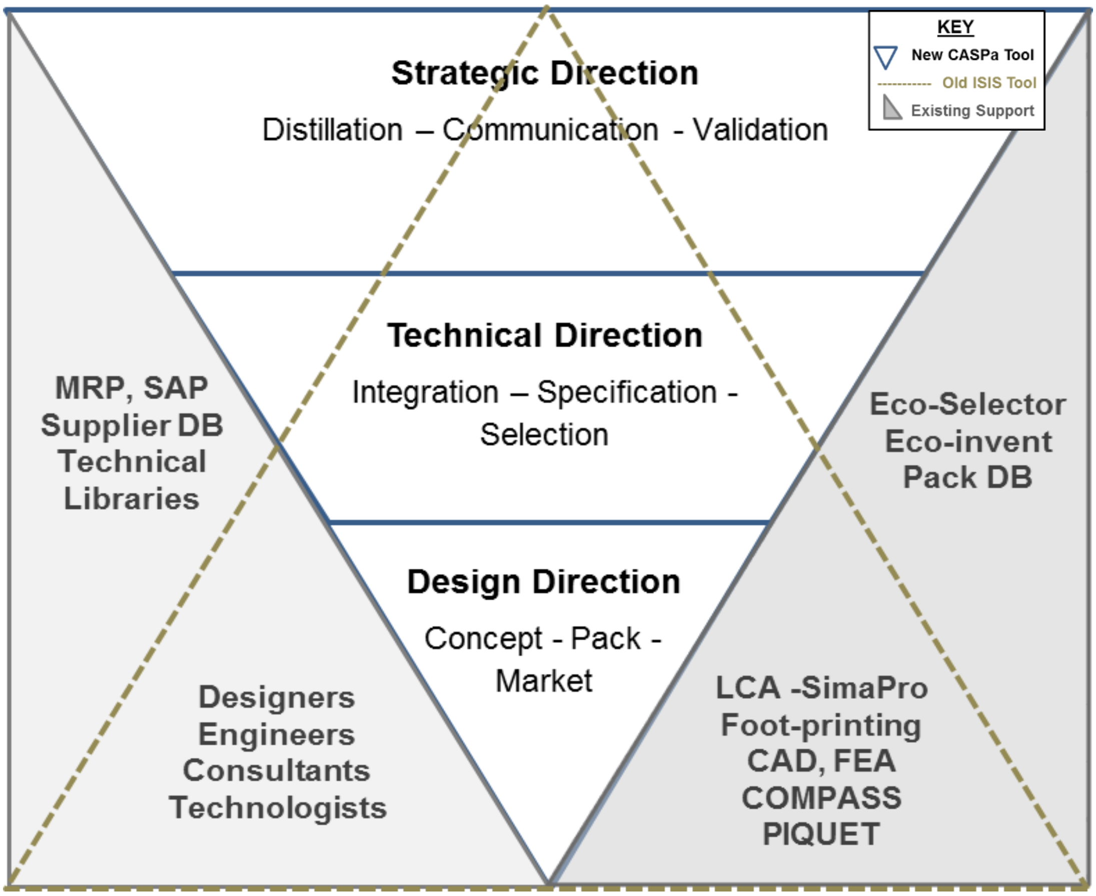


Figure 8-3: Visualisation of the CASPPa decision support tool, in relation to the initial ISIS eco-design tool.

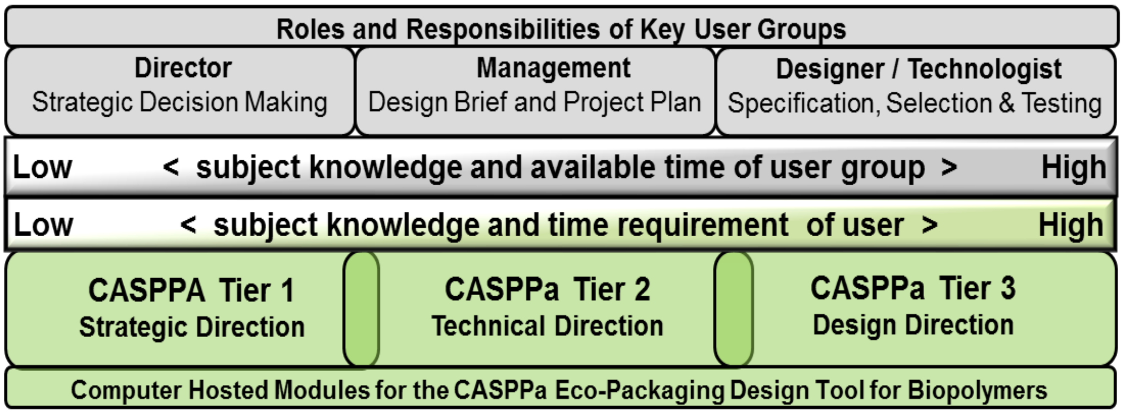


Figure 8-4: Tailoring the tool tiers to the user groups.

The main purpose and objectives of each tier are outlined below (a-c).

a) *Tier 1 – Strategic Direction:* This supports the translation of the corporate ‘sustainability’ strategy, such as a simple mission statement or detailed strategic aims and objectives, into actionable sustainable plastic packaging material and design requirements via a strategic plan. These requirements are then prioritised and detailed within a strategic packaging design specification (sPDS) which acts as an input for a feasibility assessment of the potential for biopolymers to meet these strategic requirements and as a means to communicate the strategic intent through the remaining stages of the pack design.

b) *Tier 2 – Technical Direction:* This is concerned primarily with the identification and selection of commercially available biopolymer materials and suitable supplier(s) that meet the corporate pack design specification and the sPDS.

c) *Tier 3 – Design Direction:* This provides a mechanism to assess and compare pack design at the concept and prototype stages against the original strategic intent as part of existing new pack development procedures.

The activities in each Tier are illustrated by IDEF0 diagrams in Figures 8.5 to 8.9. Figure 8-5 shows the sustainable packaging design process at the top level, whilst Figure 8.6 expands this to illustrate how this process has been developed into the CASPPa design support tool based on the three Tiers.

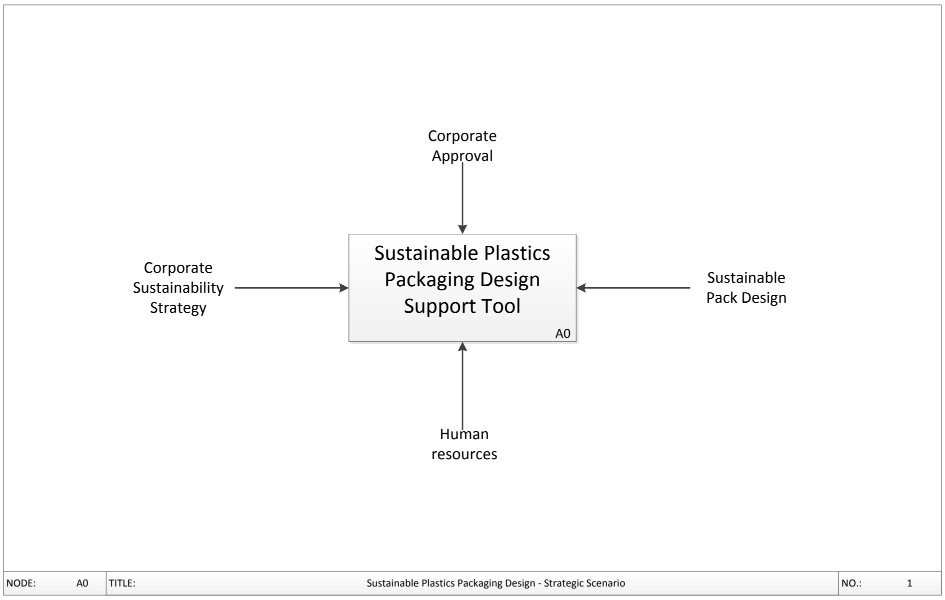


Figure 8-5: IDEF0 diagram of the Sustainable Plastics Packaging Design Process

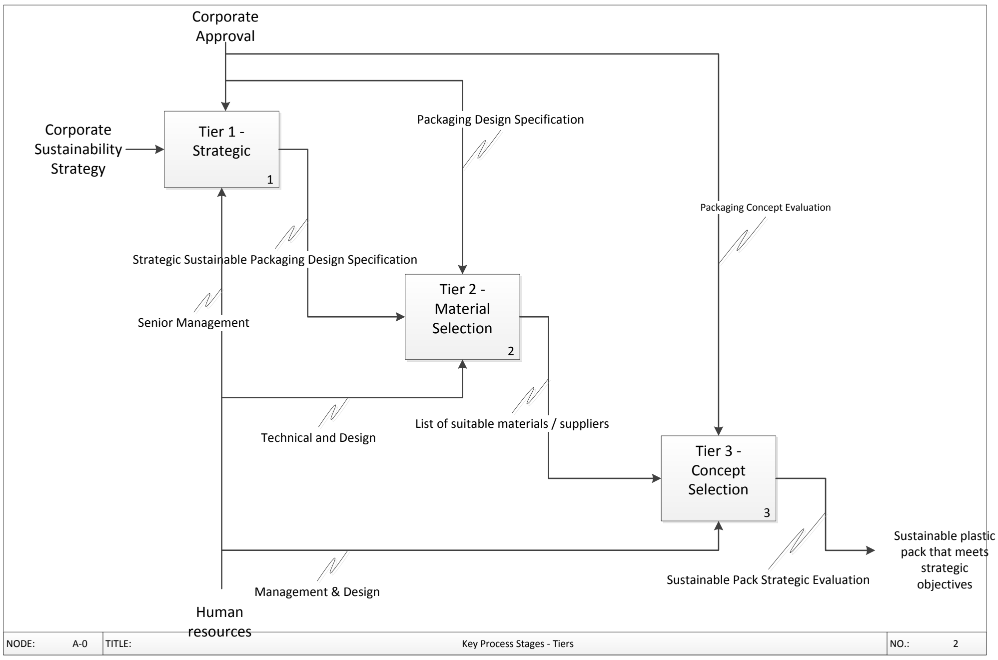


Figure 8-6: IDEF0 diagram of the CASPPa Design Support Tool

Each of the three tiers is now explored in more detail, showing the key inputs and outputs of each stage within the tier and the key resources and controls. Figure 8-7 shows the first tier which is concern with the translation, validation and communication of the corporate sustainability design strategy. Figure 8-8 illustrates Tier 2, whilst figure 8.9 illustrates Tier 3 showing how the original design intent remains undiluted during the complex and multifaceted design process.

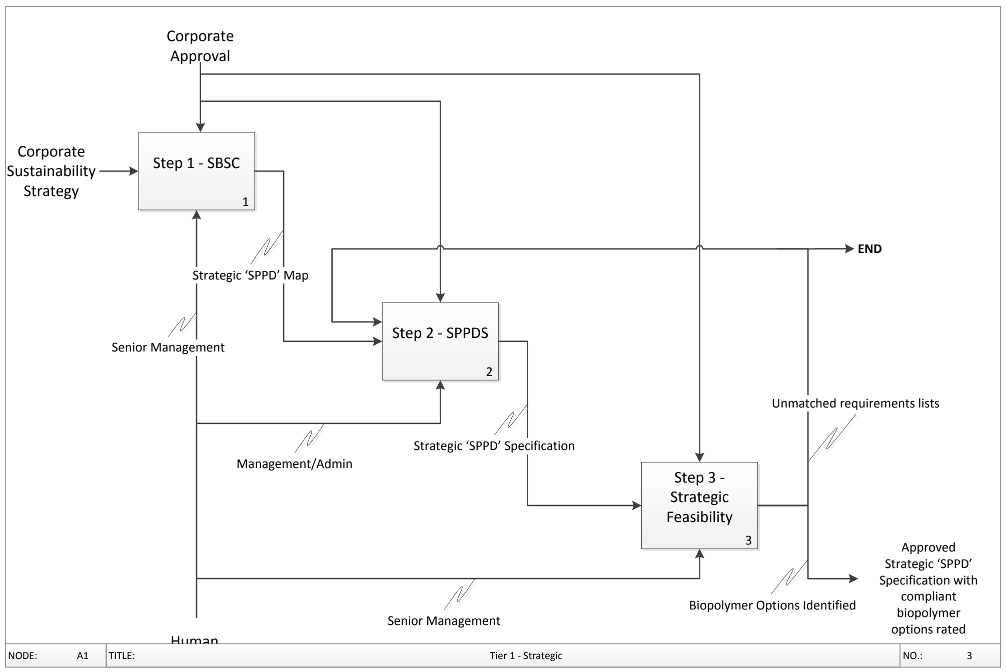


Figure 8-7: Tier 1- Strategic direction of the CASPPa Design Support Tool

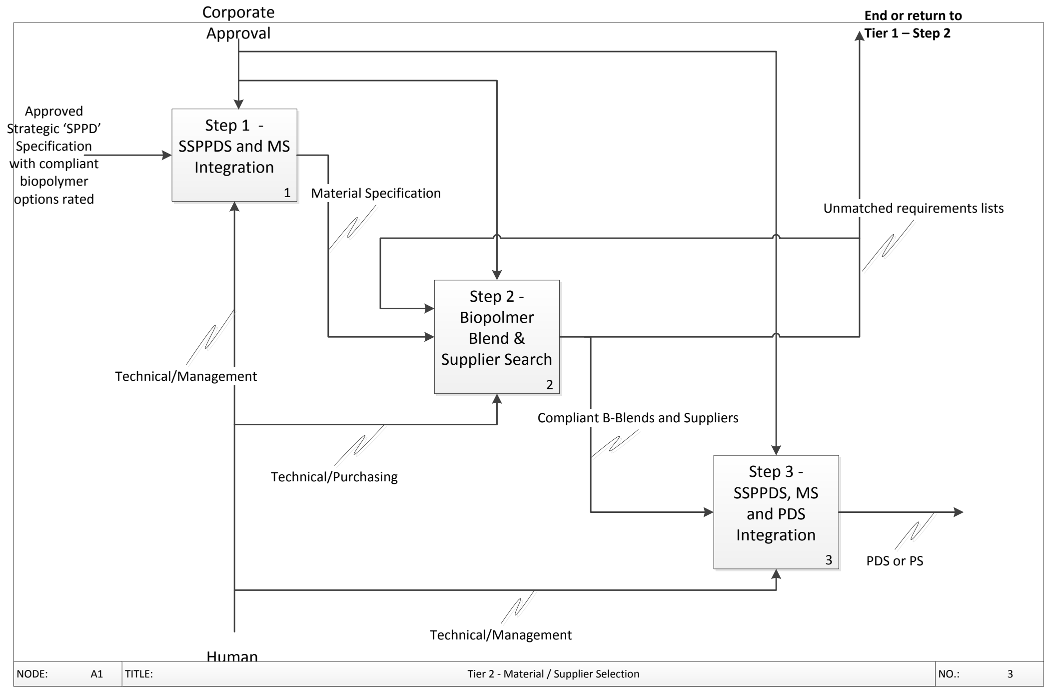


Figure 8-8: Tier 2 - Technical direction of the CASPPa Design Support Tool

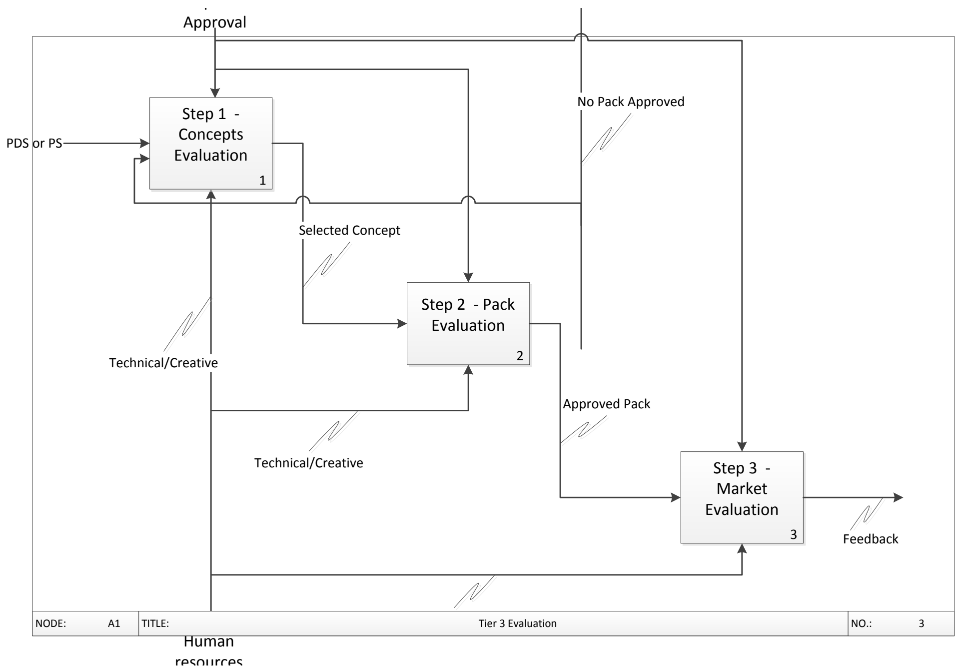


Figure 8-9: Tier 3- Design direction of the CASPPa Design Support Tool

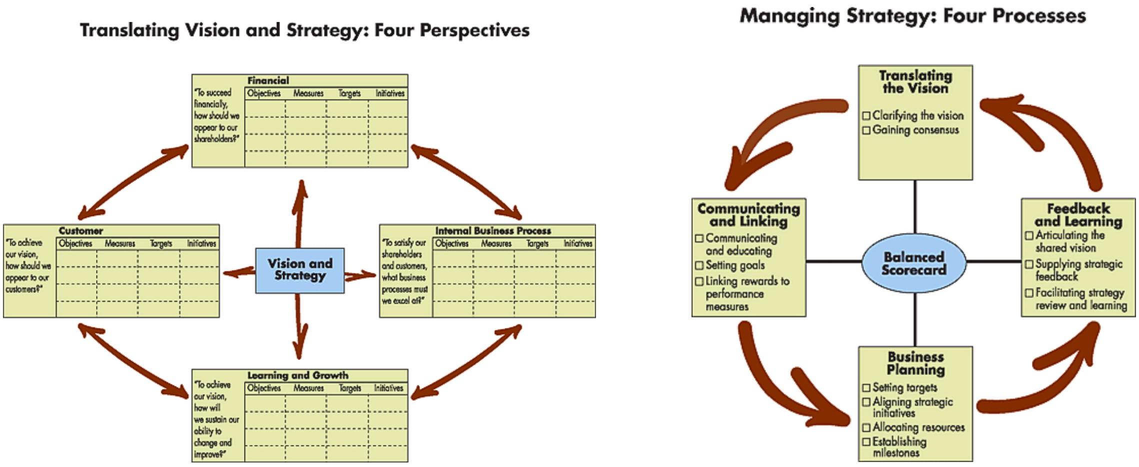
The sections 8.3, 8.4 and 8.5 describe the three tiers of the CASPPa tool in detail, explaining the process by which the framework was implemented and showing how the tool can be used in practice to support the use of biopolymers in the sustainable pack design process.

8.3 Tier 1: Strategic Direction (evaluation and communication of intent)

The framework, as described in chapter 7, highlights strategic goals as being one of the key differences between the use of biopolymers and conventional polymers. Historically, the decision to substitute one polymer type with another for a particular pack would have traditionally been made based on three key criteria, cost, technical performance or aesthetics, with one usually acting as the driver, whilst the others act as limiters. For example, if the reason or driver for the material change was to reduce costs, then the required technical performance and the aesthetics would usually become the limiting factors on how much the cost could be reduced by. Likewise if the driver was to improve the pack's technical performance (to reduce waste) or increase its appeal (improve sales or margins) then these benefits would have to be weighed against the increased unit cost (Cost Benefit Analysis). In each case the advantages and disadvantages can ultimately be expressed in one metric, the net financial impact on the business, and as such are simple to communicate within the business being easily expressed as both a strategy and operational activity. In the same way the results of these activities can also be measured and reported back in terms that are compatible with and understood by the existing financial and auditing systems, so enabling the effectiveness of the strategy to be determined. However, when trying to communicate less traditional strategic objectives such as sustainability, responsibility, and knowledge etc., as would be the case with biopolymers, the traditional financial model proved inadequate. Studies carried out by Professor Robert S. Kaplan and David P. Norton in the early 1990's concluded that increasingly, long term strategic objectives were becoming more difficult to translate into simple financial measures and targets (S & Norton, 1996). These findings led them to develop the balanced score card.

8.3.1 *The Balanced Score Card Approach*

The Balanced Score Card (BSC) was initially developed as a mechanism for assessing a company's performance beyond its traditional financial measures. Robert Kaplan's and David Norton's initial assertion was that the long term success of a company was no longer limited to financial capital but that soft factors, such as customer focus, knowledge base and intellectual property, were also key to its future success. These key factors are captured in the BSC as the four perspectives; financial, customer, learning and growth, and internal business process, as shown in Figure 8.10. It can be seen from this figure that the four perspectives are all connected, forming an integrated set of objectives and measures.



(a) (b)

Figure 8-10: The Four Perspectives (a) and Four Processes (b) of the Balanced Score Card. Source: (Kaplan & Norton, 1996)

Capturing these ‘soft’ strategic goals using the SBSC is achieved by firstly defining the strategic goals and objectives, termed ‘lagging indicators’ and the specific competitive advantages of the business that can be used to achieve these objectives, termed ‘leading indicators’. Thus for each strategic goal, the key performance drivers will be identified within each of the four perspectives. However a loose set of indicators and measures would be ambiguous and ineffective, these must be prioritized in terms of their strategic relevance. This is done by creating a hierarchical cause and effect network, linking the leading and lagging indicators (causal) towards the long term financial goals (effect), the resources of the business can be prioritized to those activities that will best promote the conversion and communication of the strategy.

This original concept of the BSC quickly evolved during its use in industry into a much broader strategic management system, linking long term strategy with short term operational actions. Whilst the initial concept of the BSC applied a primarily top down approach, three additional processes were added that linked these long term objectives with the short term actions, the four key processes as shown in figure 8-10(b) are: Translation of the strategic vision, its communication and linking to performance measures, business planning, and feedback and learning. The diagram highlights the cyclic relationship of these processes, showing how the feedback and learning phase has the potential to influence and inform the strategy providing a continuous mechanism for improvement, refinement and re-evaluation of strategic goals.

8.3.2 *Evolution of the sustainability balanced scorecard*

The functionality of the balanced scorecard, allowing non-financial success factors to be considered and incorporated within the business strategy, made it an obvious starting point for bringing corporate social responsibility and sustainability management into the heart of the business; through the inclusion of social and environmental factors into the core ‘economic’ management system. The need to reconcile these three factors or ‘pillars’ of sustainability, Social, Economic and Environmental, was noted at the 2005 World Summit (United Nations General Assembly, 2005). These terminologies evolved to reflect a more corporate perspective becoming known as the 3 Ps; People, Profit and Planet, also referred to as the triple bottom line (Elkington, 1994).

A number of approaches have been proposed on how a ‘sustainability balanced score card’ (SBSC) could be achieved (Johnson, 1998); (Bieker, 2003); (Figge, *et al.*, 2001);

(Figge, *et al.*, 2002); (Epstein & Wisner, 2001); (Schaltegger and Dyllick, 2002); (SIGMA, 2002); (Gminder & Bieker, 2002). Figge *et al.*, suggest two alternative approaches to achieving this, either by integrating the environmental and social sustainability factors into the existing four perspectives of the BSC, or introducing a fifth 'non-market' perspective. Furthermore, both of these two approaches can be extended with an additional second step incorporating the results from the higher level BSC of the strategic business unit into a 'derived social and environmental scorecard' (Figge *et al.*, 2002).

8.3.3 *Adapting the SBSC to the Biopolymer Packaging Eco-design tool*

The BSC is a tool to implement strategies, translating vision into action; it is not a tool for the formulation of strategies (Kaplan and Norton, 1997). Likewise the SBSC provides a mechanism and method for incorporating and communicating sustainability within the core business strategy and, whilst it does not itself create the strategy, its use "*may help to detect important strategic environmental and/or social objectives of the company*" (Bieker, 2003). However, the time and effort involved in developing an SBSC is considerable and usually involves significant 'learning' due to lack of the business leader's knowledge on sustainability issues and strategies.

The first 'Tier' of the biopolymer eco-design tool overcomes these difficulties by:

- Only focusing on those issues relevant to a 'plastics packaging strategy' thereby reducing the scope and complexity of the task. This minimises the senior management time required to complete the task.
- By creating a logical step by step process that is intuitive to use and thus does not require a significant degree of prior knowledge or learning.
- By providing knowledge support via a sustainable plastics packaging checklist.

In this way tier one supports the senior management to identify the strategic sustainability goals that could be supported by the use of biopolymer packaging, and to communicate these through the business using the traditional method of a packaging design brief / specification, but modified to include the strategic requirements.

The rationale for the selection of the SBSC as a starting point for a sustainable biopolymer packaging tool is that the difficulties encountered by an organisation when trying to implement a sustainability strategy at a business level are similar to the problems faced by the same organization when considering the use of biopolymer packaging. Firstly, the motivation for this change would almost certainly be based on environmental or sustainability improvement and so would lie outside the traditional financial decision making processes and secondly, whilst the technical feasibility of using biopolymer packaging is largely an operational decision, the motivation to do so is predominantly a strategic one. Ensuring that the original motivation (strategy) for using biopolymer packaging is not lost during the realization and feasibility process (action), requires the strategy to be clearly communicated and for this strategy to be realistic in terms of what biopolymer packaging can achieve. The addition of a sustainable plastics packaging checklist provides the knowledge support required by senior management during the SBSC development process.

As any business has limited resources it needs to priorities the activities of its workforce. A key requirement of this tool at this stage, in addition to minimising the senior management time to complete, is to ensure that the decision to invest significant time and resources in developing the biopolymer packaging is based on a high likelihood of success. Therefore a balance must be struck between the simplicity and brevity of using the tool (Tier 1) and the effectiveness and accuracy of the output provided. In addition to the specific sustainability requirements the output of Tier 1 should also highlight the critical ‘grey’ areas that require detailed / expert investigation before proceeding. This allows the subsequent investment of time and resources to be prioritised and to ensure that any critical issues are identified early on. Prioritisation could be achieved through a combination of LCA and cost benefit analysis.

8.3.4 *Tier 1 in practice*

Whilst the sustainability balance scorecard, developed by researchers at the University of Lueneburg in 2002 (see Figure 8-11) was aimed primarily at strategies developed for a business unit or company, it is also stated that “the SBSC is an open tool to all kinds of business strategies” (Figge *et al*., 2002).

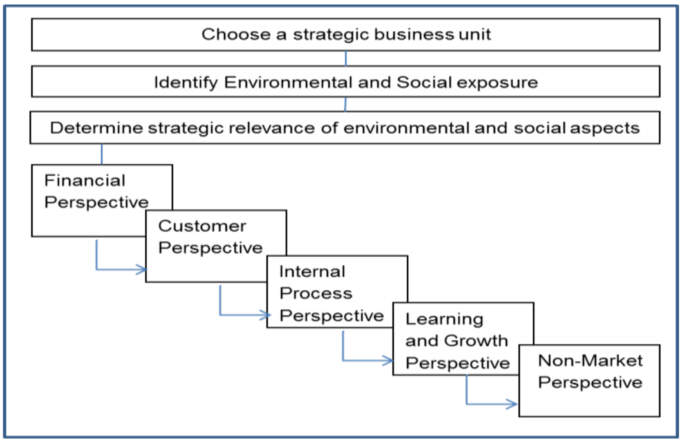


Figure 8-11: Process of formulating an SBSC. (Figge *et al*., 2002)

In the first tier of the CASPPa tool the SBSC methodology was adapted to meet the requirements of a sutainable plastics packaging design. This involved streamlining the processes to consider only packaging relevent criteria and developing an alternative output more suitable to communicating the strategic intent within a packaging design context. This Sustainable Packaging Balanced Score-Card (SPaBSC) is also supported by a Sustainable Plastics Packaging Checklist (SPPaC), to ensure that 'all' the relevent aspects of packaging sustainability are considered during the initial exposure assessment and strategic relevance evaluation as shown in the new process diagram for formulating a SPaBSC for Plastic Packaging in Figure 8-12.

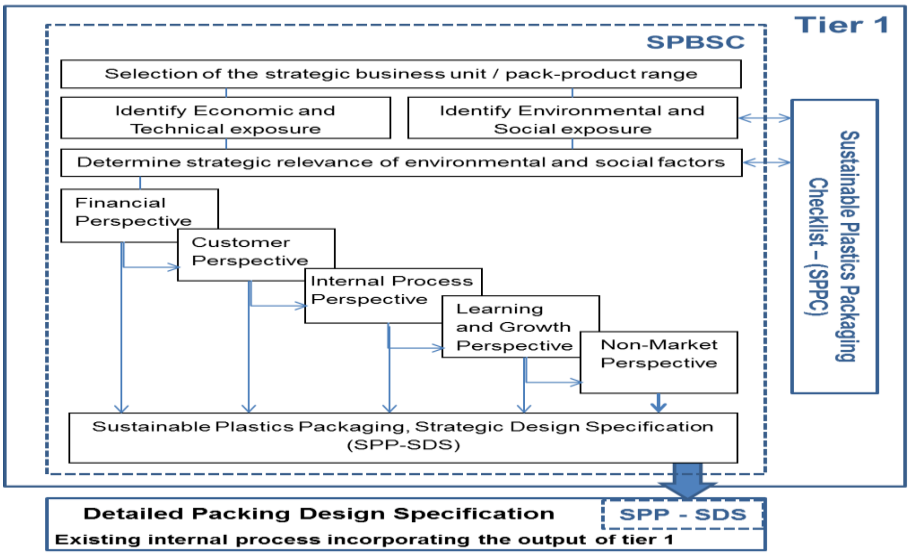


Figure 8-12: Process of formulating a Plastics Packaging SPaBSC. Adapted from: (Figge *et al.*, 2002)

A full explanation of the original SBSC methodology can be found in a number of previously published papers on this topic (Figge *et al.*, 2002; Moller and Scaltegger, 2008; Bieker, 2003), in addition practical case studies demonstrating the use of the SBSC in different organisations are also available (Woerd and Brink, 2004; Schaltegger and Ludeke-Freund, 2011). The remainder of this section will therefore concentrate on explaining the processes in Tier 1 of the tool. Firstly a description of how the original SBSC has been adapted to the SPaBSC and incorporated into the CASPPa design support tool. This is followed by a worked example, using CASPPa, of a pack development where a conventional polymer was substituted for a biopolymer. The example is based on real events known to the author who was a packaging consultant working for the company at this time, although the name of the company and sensitive data has been changed. For the purpose of the thesis, the company will be referred to as 'Furnishings Ltd'. Their corporate level strategy, described below, is the starting point for developing "Furnishings Ltd" SPaBSC. However before starting Tier 1 activities, a brief overview of the SPPC is provided in section 8.3.4.1.

The senior management team identified the need to align the company's sustainability strategy with its 'environmentally aware' customer base. It identified packaging as a key target; however the majority of product packaging was specified by their suppliers and was outside their immediate control and influence. However packaging used by its warehouse for the distribution of stock to the stores and customers was within its control. As a first step in improving its environmental footprint the company had identified its use of EPS chips as being both unsustainable and an environmental 'hazard' as, even with careful handling, there is a tendency for the chips to escape into the environment and remain there as litter due to their non-biodegradability of the plastic used to manufacture them. This problem was not limited to the warehouse operation but also impacts the stores and customers receiving postal delivery. An initial study indicated that as much as 10% of the loose fill chips were being lost into the environment, whilst the remainder was generally sent to landfill where further 'escapes' could occur. The strategic vision of the company, which encompassed this change, can be summarised as follows: "Furnishings Ltd supplies natural, ethically sourced products to an environmentally aware customer at a premium price. For our customers and shareholders we should aim to continually improve our environmental performance and where feasible use the most sustainable materials for both our products and our packaging."

8.3.4.1 The Sustainable Plastics Packaging Checklist

The SPPC is based on published data, relevant to the packaging type, within the pre-defined strategic scope. The checklist provides the key sustainable impacts that must be considered during the first stages of the SPaBSC process but does not make recommendations or provide performance data.

These key considerations are divided into sections according to the life cycle stage of the pack and for each criterion the SPPaC perspectives are listed and the likely potential impacts of strategic relevance described as shown in figure 8-13.

Sustainable Plastics Packaging Checklist			
Life Cycle Stage	**SPSC Perspective**	**Key Considerations**	**Potential impacts and likely strategic relevance**
Raw Materials	Non-Market (Environmental)	Finite Resources v Renewables	Direct and indirect depletion of finite resources. Unsustainable
	Non-Market (Social)	Food Competing	Higher food prices, reduced availability – famine/poverty
	Non-Market (Environmental)	Land and Water Use	Loss of habitat and bio-diversity, pollution, extraction, availability
	(Social)		Food production, population displacement, drought, health
	Non Market (Environmental)	Emissions	GHG / climate change, air quality, health
	Financial	Purchasing	Cost, stability, availability, choice, delivery
Polymer Production and Pack Conversion	Financial	Energy Use	…
	Internal Process	M/C Compatibility	
	Internal Process	Output	
Distribution	…		
Manufacture	…		
Retailer	…		
Consumer/Use	…		
EOL	…		
General	…		

Figure 8-13: Sustainable Plastics Packaging Checklist (part). Full version provided in Appendix 7. Adapted from The consumer goods forum, 2011; Woolworths Limited, 2010; Envirowise, 2008; Incpen 2003.

8.3.4.2 Scope – Selecting the business unit, product and pack range.

The first step of the SBSC is the selection of the business unit. In the SPaBSC this is extended to include the product and pack range. During the exercise the scope may change due to constraints, risks and other factors that are identified as part of the assessment. Where the scope is widened or changed such that the original personnel used, factors considered and and/or results obtained are no longer fully representative of the new scope, as illustrated by the set 'returnable crates' in Figure 8-14, the exercise should be re-started from the beginning. If the scope narrows such that the new scope is effectively a subset of the original one, it is only necessary to review the requirements in terms of continued relevance and priority. This could result in significant changes but should not require the addition of new considerations, thus requiring an iterative review rather than a 'fresh start'. This is illustrated by 'EPS void fill' in Figure 8-14.

In this example, as explained in the corporate level strategy in the introduction to 8.3.4, the scope of this project was selected as follows:

Business Unit: Furnishings Ltd, UK distribution centre.
Product: All products distributed in non-returnable packaging from the warehouse.
Packaging: Loose fill – Currently EPS 'peanuts'.

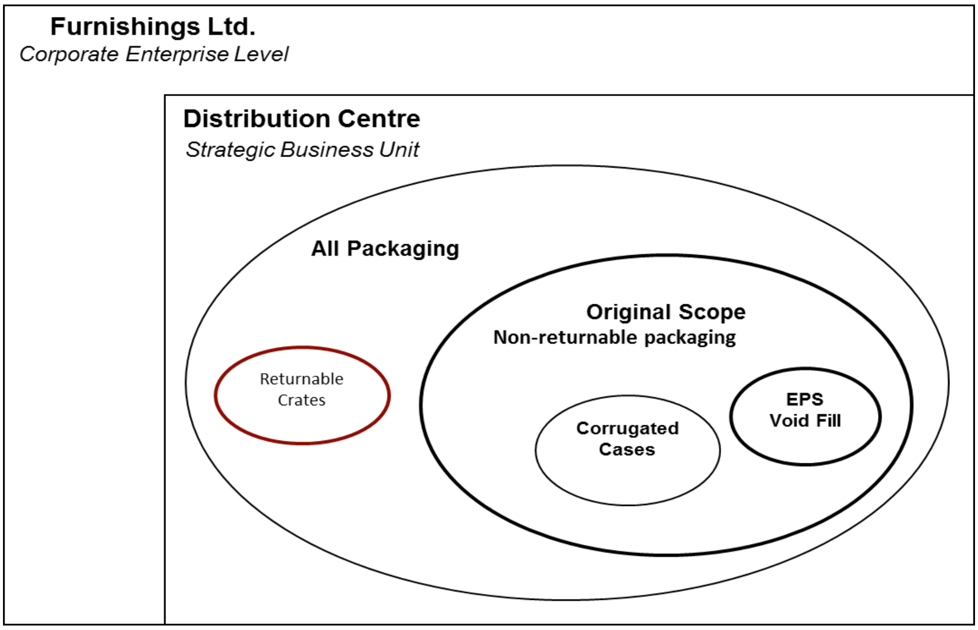


Figure 8-14: Illustration of sets within and outside the original scope.

8.3.4.3 Identification of the Economic and Technical Exposure

In Figge's original SBSC only the environmental and social exposures would be considered during this initial stage. However, in the SPaBSC economic and technical exposure has been added as the financial and technical impacts associated with biopolymer use may not be known or indeed obvious, and may even be counter intuitive. It also enables the team to begin this process in more familiar territory before considering the environmental and social exposures. Whereas the latter exposures are incorporated as 'aspects' into each perspective, the financial and technical ones are used only to inform their associated perspective and are not included as general aspects in each. Furthermore, as it is asserted that the main motivation for most companies to use biopolymer packaging is their perceived environmental benefits, it is important that such benefits are not outweighed by any economic or technical deficits that could result.

Thus, as previously asserted, the business exposures from the use of this packaging for each of these four areas need to be identified and their strategic relevance determined. The rationale for splitting these four exposures into two pairs is that environmental and social (E&S) exposures feed into all perspectives as aspects as well as being considerations within a single Non-Market Perspective. The financial and technical (F&T) exposures meanwhile inform the development of considerations within their separate perspectives. Furthermore F&T impacts are expected to be generally negatively impacted, whilst E&S would be expected to have positive impacts. Finally, F&T impacts or benefits are generally measurable and quantifiable, whilst E&S are often more qualitative and with no common metrics.

Based on previous methodologies, simple generic frameworks were developed for identifying the likely economic and technical exposure of the business arising from the use of its conventional or proposed biopolymer packaging. The first framework (Table 8-1) serves to identify the potential economic exposure of the business from a change to biopolymer packaging. To achieve this all the business activities which have a 'packaging' connection (e.g. purchasing, production) must be checked against each of the categories listed in the first column of Table 8-1, and the key considerations listed in the second column. The third column details the types of exposure that might be encountered for each. The objective at this stage is to develop a comprehensive list of all potential considerations but not to determine their importance.

Table 8-1: Economic Exposure – Key Considerations

Economic Exposure of Furnishings Ltd.'s Distribution Packaging		
Category	**Key Consideration**	**Type of Exposure**
Cost	Materials Use Storage Disposal Other	Price, current and future Amount - % of total spend Space, Losses, Hazards (fire insurance) Producer pays – PRO PRN cost Taxes – future costs (Carbon)
Supply	Flexibility Availability Reliability Security	Order quantities - minimum size Short lead times – stock item, local supply Capacity, Stock, Track record, Size Multiple sources – stability, market size
Efficiencies	Purchasing Manufacture Distribution Retail/Use	Forward pricing, Time, QA/QC Throughputs, wastage, rejects Cube, weight, damage, returns clean, reliable, ease of access, disposal

In a similar approach to the development of these economic considerations, as presented in Table 8-1, so the potential technical exposures need to be identified. In the chosen example of an EPS loose fill used by the warehouse staff for orders despatched in non-returnable packaging, the main function of the packaging is to provide adequate cushioning protection to the products during transit. As such the company's exposure is limited mainly to the storage, handling, use and disposal of the material, with few production, marketing or consumer issues. Table 8-2 presents the results of this step for the chosen company example.

Table 8-2: Technical Exposure – Key Considerations

Technical Exposure of Furnishings Ltd.'s Distribution Packaging		
Category	**Key Consideration**	**Type of Exposure**
Storage	Shelf Life Conditions / type Risk Handling	Use by, robustness, inert Special storage requirements Fire, Contamination Weight, fragility
Production	Compatibility	Works with existing processes / equipment
Use	Warehouse Distribution Retail/Use	Throughputs, wastage, rejects Cube, weight, damage, returns Out of date, Single use
Disposal	Managed Un-managed	Options available – reuse, recycle Litter (Land and water) - degradable

8.3.4.4 Identification of the Environmental and Social Exposure

The objective of this step is to obtain a comprehensive list of all the strategically relevant environmental and social interventions that could originate from the business unit from the use of its current or proposed packaging. The basis for this is that these interventions are ultimately responsible for the environmental impacts caused by the business unit's use of this packaging. Heijungs defines an environmental intervention as "a change in the environment directly caused by human activities" and asserts that "all environmental problems can be traced back to a physical or chemical intervention" (Heijungs, 1992). In order to identify the business unit's environmental exposure from the selected packaging, all the key considerations and associated pertinent environmental interventions should be considered against the categories listed in the first column of the table (Table 8-3).

In this particular example for Furnishings Ltd, having established the scope, corporate level strategy and the technical and economic exposures, is to identify the important environmental aspects (Figge, et al., 2002). As before this is done without attributing their strategic relevance with the emphasis on ensuring a comprehensive list of the relevant environmental aspects and impacts. This will also form the basis of the next step of integrating these into the SPaBSC.

Table 8-3: Environmental Exposure – Key Considerations

Environmental Exposure of Furnishings Ltd's Distribution Packaging		
Category	**Key Consideration**	**Interventions**
Resource Consumption	Materials Land Use Water Use Energy	Amount, Type, Depletion, Toxicity Mainly during raw material production During extraction/production of raw materials Manufacture of chips
Emissions	GHG's To Air To water To Land	CO2 , methane VOC's, dust Pollution – oil, plasticisers, particulates Litter, contamination
Efficiencies	Manufacture Distribution Retail/Use	Throughputs, wastage, rejects Cube, weight, damage, returns Out of date, Single use
Waste	Managed Un-managed	Landfill or incineration Litter (Land and water)

To assist the management of Furnishings Ltd in carrying out this task and to ensure that all possible interventions are considered the SPPaC, introduced in section 8.3.4.1, is used to complete this task. For each environmental category, assisted by the SPPaC, the management must decide which impacts are relevant to the use of its packaging and what is their environmental impact. In this example the environmental impacts of Furnishings Ltd. results in the profile of environmental exposure as summarised in Table 8-3. It is apparent from this that resource use, GHG emissions and managed/unmanaged disposal are dominant interventions.

The social exposure is considered slightly differently to the other three aspects due to their diversity and variety. Social aspects lack the common foundation that is available for the other previous aspects and as a result no comprehensive classification is available; such as used to compile the environmental impacts in the SPPaC. As with the SBSC (Figge, et al., 2002), the SPaBSC follows this convention of classifying the social aspects according to the actors involved. This implementation of this stakeholder based framework for Furnishings Ltd. can be seen in Table 8-4. These stakeholders are subdivided into ‘direct stakeholders’, which are related to the company by direct material exchange and ‘Indirect Stakeholders’ which are not. These four tables 8-1 to 8.4, and the corporate level strategy, form the basis for developing the SPaBSC for Furnishings Ltd.

Table 8-4: Social Exposure – Key Considerations

Social Exposure of Furnishings Ltd.’s Distribution Packaging		
Actors	**Direct Stakeholders**	**Indirect Stakeholders**
Internal	Furnishings employees - Job Security & Working Conditions	
Suppliers	Suppliers - Long term relationships, partnerships and Joint venture	Job Security and Working Conditions of supplier employees
Customers	Purchase Cost Product quality Health and safety	Health and safety – handling
Community	Shoppers – clean environment	Social decay - Litter
Societal	Resource availability Food supply	NGO’s - Human Rights - Labour Government - Unemployment and regional development Council - Litter

8.3.4.5 Developing Key Indicators for Strategically Relevant Aspects.

In accordance with the methodology for Figge's original SBSC, the next stage of the SPaBSC is the identification and alignment of the strategically relevant aspects, described by Figge as, "to translate the verbally formulated strategy of a business unit into a causally linked objectives and indicators" (Figge, et al., 2002). Following a methodology developed by Kaplan and Norton (2001) in the original BSC, a top-down approach was taken to the formulation of the SPaBSC, with the addition of the environmental and social perspectives as proposed by Figge et al. (2002), and the specific packaging related technical and commercial aspects in the SPaBSC. This top-down approach, starting with the financial perspectives, ensures the "hierarchical and causal linkage of the strategically relevant aspects" (Kaplan & Norton, 1992).

The strategically relevant aspects generally fall into one of three types: Strategic Core Issues; Performance Drivers; or Hygienic Factors. For the first type, Strategic core issues, lagging indicators need to be defined which will be used to measure the achievement of the strategic core requirements as identified in the perspectives. A generic set of lagging indicators were developed by Kaplan and Norton (1996) and are presented in Table 8-5. How these lagging indicators will be achieved is shown by performance drivers which are represented by the leading indicators as shown in Table 8-6. Hygienic factors are ones which must be met, but do not offer a competitive advantage, such as legislation compliance, and therefore do not form part of the company strategy or thus SPaBSC.

Table 8-5: Development of Lagging Indicators. Source: (Kaplan & Norton, 1996)

Financial perspective	Customer perspective	Process perspective	Learning & growth perspective	Non-market perspective
• Revenue growth • Productivity growth • Asset utilization	• Market share • Customer acquisition • Customer retention • Customer satisfaction • Customer profitability	• Innovation process • Operations process • After-sales service process	• Employee retention • Employee productivity • Employee satisfaction	• Freedom of action • Legitimacy • Legality

Table 8-6: Development of Leading Indicators. Source: (Kaplan & Norton, 1996).

Financial perspective	Customer perspective	Process perspective	Learning & growth perspective	Non-market perspective
	• Product attributes • Customer relationship • Image and reputation	• Cost indicators • Quality indicators • Time indicators	• Employee potentials • Technical infrastructure • Climate for action	*Leading or lagging indicators from all other perspectives*

8.3.4.6 Developing the Perspectives

It is important to consider how the objectives and measures of upper perspectives can be attained when considering the other perspectives in a top-down approach as shown earlier by the cascading perspectives in Figure 8-12

Financial Perspectives

These perform a dual role in the SPaBSC by defining the financial performance a strategy is expected to achieve, whilst acting as an endpoint of the cause and effect chain for other perspectives (Kaplan & Norton, 1996). In this example, Furnishings Ltd. financial perspectives are shown in Figure 8-15. The Top Financial Measure (TFM) will be the determining factor that will often form the key justification for an investment of a company’s time and resources. In this example the company is committed to improving its sustainability of which financial impacts are a key part, as such the minimum financial return expected is to recoup the cost of the investment in any environmental initiative which includes development time. Setting the bar low ensures that progress can be made but retaining some degree of financial accountability.

Customer Perspectives

In this perspective it is important to identify the key client segment that is being targeted in order to achieve the desired result and which value proposition is being marketed. As with the BSC, it is essential that the measures and objectives are linked to the objectives of the financial perspective (Kaplan & Norton, 1996).

In this example (Figure 8-16), two lagging indicators have been identified within the strategic core issues as increasing sales and customer satisfaction. The objective of increasing sales by 12% is intended to achieve the financial objective of growing turnover by 12%. It is asserted that customer satisfaction will be a key factor in achieving this so this is included as the other lagging factor.

Financial Perspectives **Furnishings Ltd** **2013**	**Measures and Lagging Indicators**
	TFM **Return on Investment (ROI) of 8-10% over 2 years**
	Achieved by:
	Turnover Growth of 12% over two years
	Whilst, maintaining profit margins at 20%

Figure 8-15: Financial Perspectives

The leading indicators show how Furnishings Ltd intend to achieve this through its distribution packaging. Ensuring that the goods arrive in top condition avoids customer complaints and lost sales due to returned goods and cancelled orders. The technical performance of the biopolymer as a cushioning material will be a key factor in achieving this success, ensuring that goods received by the customer are of the same quality as those despatched from the warehouse. Primary and secondary market research has also identified a problem with excessive packaging. Customers receiving goods have complained that sometimes there seems to be more packaging than product. EPS chips are a particular gripe, as they tend to escape into the environment and remain visible there for years. There is an obvious dichotomy here between sufficiently protecting the product and using only the minimal packaging. Current packaging waste legislation already dictates that packaging should be minimal and the company has taken steps to comply with this. Therefore it was decided to focus on pack disposability as a means to meet customer needs without compromising on product quality.

The company also has links with NGO's and has been involved with them on projects, such as the shipper light weighting exercise and an LCA of its cotton products. It considers itself to be a social and environmentally responsible company and sees this as a core part of its corporate image and brand values.

Customer Perspectives Furnishings Ltd 2013		**Environmental Aspects**				**Social Aspects**			
						Direct		**Indirect**	
		Emissions	Waste	Material Input / intensity	Energy Efficiency	Internal	Value Chain	Value Chain	Societal
Strategic core issues	Increase Sales Objective 12%								
	Customer satisfaction						• Customers		
	Product attributes								
Performance drivers	Protects products Easy disposal		Avoids Litter	Minimal material			• Customers		
	Customer relationship								
	Image and reputation								
	Environmentally and socially responsible						• Customers		• WRAP • FOE

Figure 8-16: Customer perspectives of Furnishings Ltd.

Internal Process Perspectives

As highlighted in the cascading model, this perspective links to the previous two perspectives of Financial and Customer. The objective is to identify the processes needed to achieve the targets of the higher perspectives and in doing so establish the causal links to them from the internal process perspective. The lagging and leading indicators are shown in Figure 8-17. It is clear that the company are concerned about reduced quality and performance of a novel material like biopolymers. A key requirement is to ensure that in solving one issue other bigger problems are not introduced. The packaging is a fraction of the cost, value and impact of the total shipment and it is essential that product quality is maintained. However the company prides itself on being a market leader and is a keen adopter of novel technologies that improve its environmental performance. A further concern that has been identified is the competition of biopolymers with food and this should be avoided.

Internal Process Perspectives Furnishings Ltd 2013		**Environmental Aspects**				**Social Aspects**			
						Direct		**Indirect**	
		Emissions	Waste	Material Input / intensity	Energy Efficiency	Internal	Value Chain	Value Chain	Societal
Strategic core issues	Innovation process								
	Novel solutions								
	Packing/Production process								
	Total cost			• Yield					
	Service process								
	Fit for purpose		• Performance						
	Easy disposal		• Bio-degradable						
Performance drivers	Quality control and security of supply		• Shelf Life	• Minimal material				• Fair Trade	• Non Food
	Purchase price								
	Protection and performance		• Avoids Damage						
	Alternative EOL options		• Avoids Litter						
	Resource Use			• Efficient					• Non Food

Figure 8-17: Internal process perspectives for Furnishings Ltd

Learning and Growth Perspective

This describes the infrastructure that is required to achieve the other perspective objectives. Employee motivation is a key factor in any business success and rather than use external consultants to undertake this development, key individuals were given the opportunity to develop skills and take responsibility for researching, testing and implementing the changes. This process increased communication between different departments that previously had been lacking and gave employees a sense of ownership and achievement in 'Making a Difference' to their business and the wider environment. Figure 8-18 shows the key leading and lagging indicators and how these feed into the other perspectives.

Non-Market Perspective

Finally, the strategic relevance of the environmental and social factors has to be checked. Where factors are identified that could influence the market success of the company, they should be introduced into this non-market perspective. One method for deciding this is to answer a series of questions as developed by Figge *et al.* (2002). These questions are reproduced in the following text and the results from the answers are provided in Figure 8-19. A more detailed walk-through of this process is provided within the case study in chapter 9 and so will not be duplicated here.

Learning and Growth Perspectives Furnishings Ltd 2013		**Environmental Aspects**				**Social Aspects**			
						Direct		**Indirect**	
		Emissions	Waste	Material Input / intensity	Energy Efficiency	Internal	Value Chain	Value Chain	Societal
Strategic core issues	Employee satisfaction					• Employees			
	Development								
Performance drivers	New Skills	• Novel							
	Workplace								
	Healthy and Safe	• Dust							
	Culture								
	Shared Group Values	• Litter							

Figure 8-18: Learning and growth perspective for Furnishings Ltd.

Non-Market Perspectives Furnishings Ltd 2013		**Environmental Aspects**				**Social Aspects**			
						Direct		**Indirect**	
		Emissions	Waste	Material Input / intensity	Energy Efficiency	Internal	Value Chain	Value Chain	Societal
Strategic core issues	Labour								
	Working Conditions							• Employees of raw material suppliers	• Human Rights
	Material								
	Non Food								• Food Cost
	Disposal								
	Non Littering		• Biodegrades						

Figure 8-19: Non-Market Perspective for Furnishings Ltd.

Questions to determine strategic relevance, as proposed by Figge *et al.* (2002).

- “Are there any environmental or social aspects which influence the success of ‘the company’ via non market mechanisms?”
- “Do these environmental or social aspects represent strategic core issues at which ‘the company’ has to excel in order to successfully execute its strategy?”

“What is the substantial contribution of the strategic non-market aspects to the achievement of ‘the company’s’ strategy?”

8.3.4.7 The Strategy Map

The final step in the BSC and SBSC is usually to show the results graphically in a strategy map. The strategy map for Furnishings Ltd. is presented in Figure 8-20 and shows the causal links between each of the perspectives developed in this chapter. However whilst this is useful in communicating the alignment and relevance of the strategic goals within a business context, to feed into a design process and enable the selection of a suitable biopolymer that meets the requirements a measurable set of requirements need to be defined within a ‘Strategic’ packaging design specification, which is discussed in the following section.

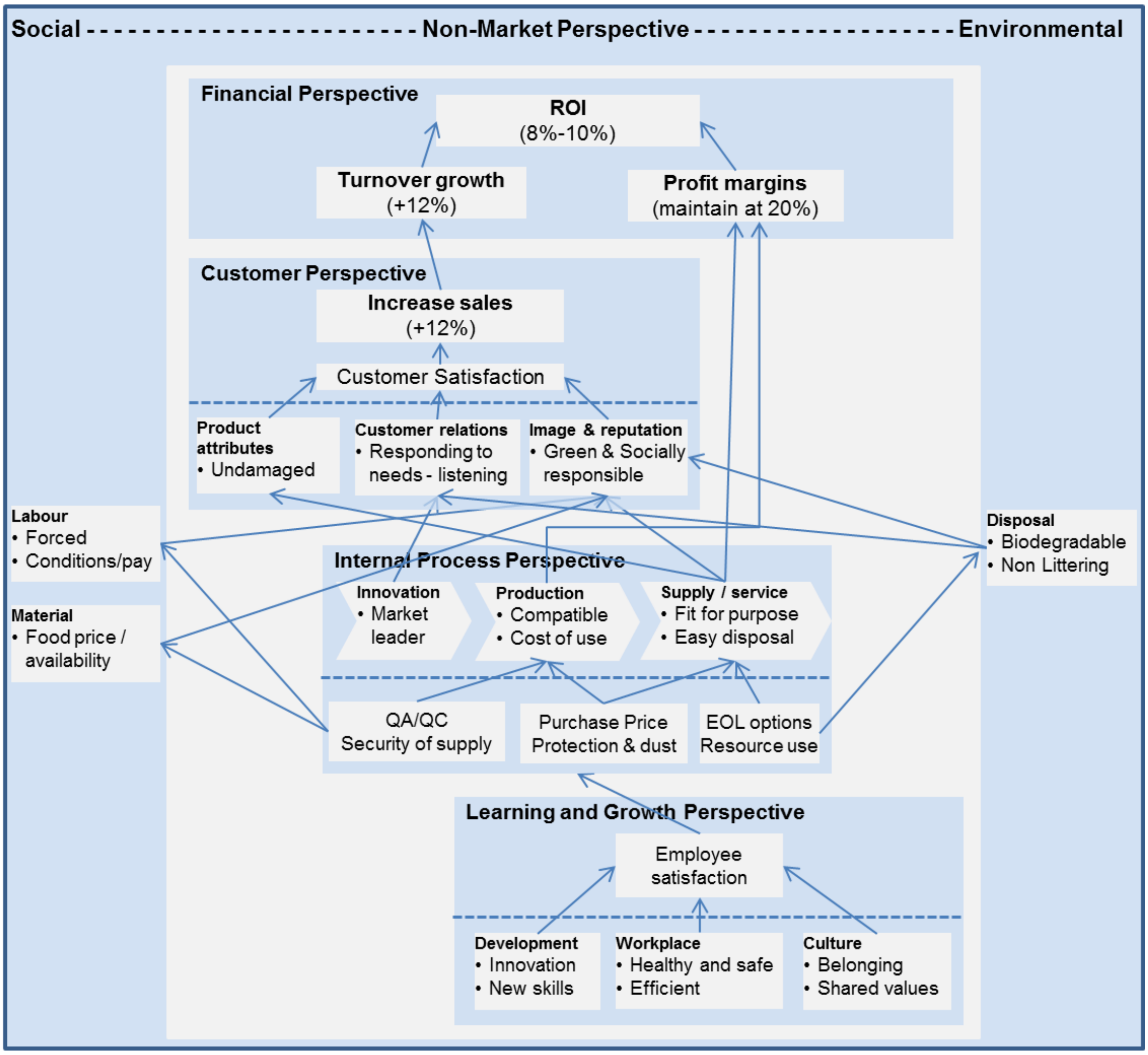


Figure 8-20: Strategy map for Furnishings Ltd.

8.3.5 *The Strategic Packaging Design Specification*

This is developed from the perspectives and will use generic performance criteria as defined in the checklist and also used as data headers in the database. As can be seen from Table 8-7, in addition to incorporating the key requirements from each perspective into the specification, these have also been prioritised. Prioritisation is potentially a subjective process and it could be argued they should all be high, however it is encouraged that within each perspective, the requirements are initially ordered to indicate which is more important. Then these are checked against each other to ensure that the prioritisation is right between perspectives. Once achieved the next step is to identify the potential of biopolymers to meet these objectives.

Table 8-7: Strategic Packaging Design Specification

Strategic Packaging Design Specification			
Perspective	**Considerations**	**Specification**	**Strategic Importance High Med Low**
Financial	• ROI		• High
Customer	• Deliveries • Environmentally and socially responsible image.	• No loss of quality of goods delivered or excessive packaging disposal. • Avoid litter and excessive packaging waste	• High • Medium
Internal Process	• Material cost • Performance • Efficiency	• Maximum 10% increase • Fit for purpose - Damage • No loss of efficiency	• Medium • High • Medium
Learning & growth	• Employee satisfaction	• Health and safety • Novel Material	• High • Low
Non-market Environmental	• Litter • Resource depletion	• Biodegradable • Renewable	• High • Medium
Non-market Social	• Food availability • Forced labour	• Manufacture does not use food grade raw materials • Complies with international employment law and human rights	• Medium • High

8.3.6 *Strategic Feasibility*

Once the strategic specification has been completed, a quick review of the strategic objectives against the potential for biopolymers to contribute is required, before the specification passes through to the next tier of the CASPPa tool. This is to ensure that the expectation of the business is in principle feasible before committing significant business resources to its selection, development, trialling and implementation. This initial stage uses a combination of the multi criteria decision making process AHP as described in the review chapter 5, and technical data obtained from external databases. A brief description of how the AHP process was implemented at this stage follows.

8.3.6.1 Using AHP to score biopolymer performance against key specification criteria

As with conventional polymers, the biopolymers used for packaging are based on just a small range of unique types; the most notable being PLA, PHA, PHB, RC, Bio-PET, bio-PE and TPS, however, depending on the manufacture and additional materials used, a much larger range of 'blends' can be produced each with slightly different performance characteristics and impact criteria. The formulation of these commercial 'brand name' biopolymers will be confidential to the companies and whilst some information is available in data sheets, more detailed information would not be available for publication. This makes it difficult to assess the biopolymers and populate the database with the correct information that might allow initial feasibility and primary selection to take place.

To-date there are many (500+) commercially available biopolymer blends for manufacturing plastics packaging, and this is increasing and changing as new ‘products’ are launched and old products improved, too many and too complex to provide a detailed assessment of. Instead a two stage approach is used firstly determining a basic feasibility and identifying a key group and then providing a more detailed selection based on the criteria available within the group.

Allocate using AHP performance values for range of assessment criteria available. AHP will use a weighting based on the skill /knowledge of the assessor. The assessor allocates a score to the polymer based for that question/criterion and then states his/her confidence in making that assessment. An example of a completed questionnaire is given in Table 8-8. In reality the questionnaire would contain multiple questions.

The rationale for listing a range of polymers under one question, rather than many questions grouped under one polymer, is that it allows the assessor to judge the performance of each polymer relative to the others (e.g. PLA is more degradable than PHB but less than TPS), so providing a reference point to give greater consistency and accuracy of the responses.

Table 8-8: Completed Survey Question - Example.

(AHP-SF) Biopolymer Performance Survey Form				
Question 1a: How easily will packaging (Plastic bag or bottle) made from this polymer biodegrade in the environment (assume temperate conditions)				
Assessor (Overview Job and experience)	**Polymer** (Types not grades)	**Score 1-5** 1 – Very well 5 - Not at all	**Confidence** High, Med or Low	***Weighting*** *(Office use only)*
Converter with 5 years’ experience of blow moulding PET, PE and PLA bottles	PLA	3	High	3
	PHA / PHB	3	Low	0
	RC	-	-	0
	Bio-PET	5	High	3
	Bio-PE	5	High	3
	TPS	1	Med	1

The confidence factor is used to weight the final score so that a high confidence triples the impact of that score in the final average, whilst a medium counts only once and anything less (low or blank) is simply excluded. This is exemplified in Table 8-9 where the 3rd column 'scores multiplied by confidence' illustrates how a weighted score is calculated. For this example a number of surveys were populated and the results entered into the final score calculation table, Table 8-9.

So for the first biopolymer PLA, 3 assessors responded as follows:

Assessor 1: Score = 3, Confidence = High
Assessor 2: Score = 2, Confidence = Medium
Assessor 3: Score = 1, Confidence = Low

To calculate the weighted score the initial Score is multiplied by the Confidence Factor (CF), for High this is x3, Medium x1 and Low x0

Assessor 1 weighted score = 9 (Score 3 x CF 3)
Assessor 2 weighted score = 2 (Score 2 x CF 1)
Assessor 3 weighted score = 0 (Score 1 x CF 0)

The final weighted score is then calculated by summing the individual weighted scores and dividing them by the sum of confidence factors. In this example this would give:

Sum of weighted scores = 11
Sum of CF's used = 4
Final weighted score = 11/4

A similar process was used to calculate the FWS of the other biopolymers as shown in Table 8-9.

Table 8-9: Calculating the final weighted score from multiple responses

<table>
<tr><th colspan="5">(AHP) Biopolymer Performance Final Weighted Score</th></tr>
<tr><td colspan="5">Question 1a: How easily will packaging (Plastic bag or bottle) made from this polymer biodegrade in the environment (assume temperate conditions)</td></tr>
<tr><th>Total Assessors</th><th>Biopolymer</th><th>Scores Multiplied by Confidence (only +positive scores count)</th><th>Final Weighted Score (FWS)</th><th>Standard Deviation</th></tr>
<tr><td>3</td><td>PLA</td><td>(3+3+3)+(2)+(0) = 11/4</td><td>2.75</td><td>0.43</td></tr>
<tr><td>2</td><td>PHA / PHB</td><td>(0)+(5) = 5/1</td><td>5</td><td>0</td></tr>
<tr><td>1</td><td>RC</td><td>(0) = no result</td><td>-</td><td>-</td></tr>
<tr><td>4</td><td>Bio-PET</td><td>(5+5+5)+(5+5+5)+(0)+(4) = 34/7</td><td>4.9</td><td>0.35</td></tr>
<tr><td>4</td><td>Bio-PE</td><td>(5+5+5)+(5+5+5)+(0)+(4) = 34/7</td><td>4.9</td><td>0.35</td></tr>
<tr><td>3</td><td>TPS</td><td>(1)+(1+1+1)+(3) = 7/5</td><td>1.4</td><td>0.8</td></tr>
</table>

The next step is to establish a confidence factor for the FWS. The key factors that would contribute to this would be the sample size - derived from the number of assessors and their individual confidence in answering the question, and the general agreement / consistency of the responses – derived from the standard deviation of the scores given. The standard deviation for each biopolymer was calculated using the following formulae:

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \mu)^2}$$

For PLA in Table 8-9 the scores used would be 3, 3, 3, and 2, for which the standard deviation is 0.43. Scores of zero (low confidence) are omitted from the standard deviation calculation.

The sample size is based on sum of confidence, for the PLA example used above, this would be 4 (3 + 1). This is a very small sample size so although the standard deviation of 0.43 is good the small sample size would not give a great deal of confidence in this result. To interpret these two results the following table is used (Table 8-10). As can be seen the combination of a sample size <10 and a STD of 0.43 results in the recommendation that for this score PLA 2.75 (Table 8-9), if it is high priority, the sample size should be increase, otherwise the score is acceptable to be acted on at this stage.

Table 8-10: Interpretation of AHP results at strategic feasibility stage.

		Sample Size Based on Sum of Confidence, *SC*		
		Small SC < 10	Medium SC = 10 to 25	Large SC > 25
Std Deviation of Scores	**Low σ(S) < 1**	High priority criteria increase sample size otherwise acceptable	**Reliability Good** **OK to Proceed**	**Reliability Excellent** **Good to Proceed**
	Average σ(S) = 1 to 1.5	High and medium priority criteria increase sample size otherwise acceptable	High priority criteria increase sample size or independently validate, otherwise ok	High and medium priority criteria Independently validate e.g. LCA
	High σ(S) > 1.5	**Unreliable** Increase sample size	**Unreliable** Increase sample size or independently validate e.g. LCA	**Unreliable** Independently validate e.g. LCA

8.3.7 *Tier 1 Discussion*

Tier 1 of the CASPPa tool began by taking the top level corporate strategy and applying it to a selected packaging area. The tool provided a structure to support and facilitate the process of converting this into specific operational terms that could then be communicated to the business through a strategic packaging design specification. However before proceeding with the second stage of selecting materials and suppliers, the strategic packaging design specification is checked against the strategic database, populated using AHP process, to determine if the strategic aims and objectives intended to be achieved by the use of biopolymers for the packaging selected is realistic and potentially feasible. If it is decided that the identified strategy cannot be delivered, this can be reviewed and a decision made either to modify the strategic goals or not to proceed to the next stage. This means that only projects with a high likelihood of meeting the criteria will progress, so increases the chances that the pack design that eventually makes it to market is more likely to contribute towards the company's overall strategic goals.

8.4 Tier 2: Technical Direction

With over 500 biopolymer resins available commercially, each with a unique set of technical and performance characteristics, finding the optimal biopolymer material for a packaging application can be a complex task. Tier 2 of the CASPPa tool provides technical direction, and offers a mechanism for identifying which commercially available biopolymers meet the environmental, technical, commercial and operational requirements of the intended application. This is different to the strategic feasibility conducted at the end of Tier one which looked more generally at the properties of different biopolymer types and not specific formulations. There are three key steps in Tier 2 as indicated in the IDEF0 diagram in Figure 8-8: Tier 2 - Technical direction of the CASPPa Design Support Tool. These three steps, there inputs and outputs and process are described in more detail in the following sections. The first step involves integrating the requirements listed in the 'strategic' Packaging Design Specification (sPDS) with the companies standard 'technical' Packaging Design Specification (tPDS).

8.4.1 *Integration of the sPDS into the company's tPDS.*

The first step on receiving the approved sPDS would be to integrate the key requirements into the companies own existing specification process. At this stage it is a requirements specification not a material specification, in other words it is a list of desirable and essential attributes that are required rather than the actual performance characteristics of a particular material. The purpose of the company's tPDS is to ensure that the subsequent design concepts developed from the tPDS are commercially and technically viable. The level of detail and how it is recorded will vary from company to company and the specifications are often created through a consultation process with key employees from the various departments. In addition to the requirements identified in the sPDS, a number of other requirements will need to be specified. To illustrate this a particular requirement from the sPDS will be selected and its expansion and integration into the company's tPDS will be illustrated. It is also worth noting that the sPDS will remain in its original form as an attachment to the tPDS as it will be required to assess the future designs against both, the original strategic intent and the full tPDS.

In the example of Furnishings Ltd, two of the key requirements listed in the sPDS (Table 8-7) were 'No Loss of quality of goods delivered' and 'No loss in packaging and transport efficiency'. Clearly these are important criteria and need to be incorporated in the tPDS, however these need to be described in terms that can be used to conduct a database material search. In the chosen examples trials would need to be conducted to confirm performance, but it would not be practical to trial every material in the initial instance so the key properties of the material that are likely to be important need to be identified and specified. For the two requirements selected the following technical specifications were established:

Bulk Density (KG/m3) = 6.0 to 9.5
Friability = 0.003% to 1.8%
Resilience = 85% to 100%
Compressive stress MPa = 0.05 to 0.16
Glass transition = 60°C
Shape = Interlocking

Using these technical specifications, it is possible to search the database to identify suitable materials. However, due to the number of potential variations a test procedure would be required once a material had been identified.

8.4.2 *Tier 2: Database Material and Supplier Search*

The initial sPDS search identified a particular material group such as TPS, or even expanded TPS peanuts. The next step of the process requires a material search against a technical database of commercial biopolymers to identify the most appropriate options.

The CASPPa database consists of three modules: a User Interface Module (UIM), a Data Module (DM) and a Processing Module (PM). A prototype for this Tier was constructed using Microsoft Excel and Access, although it is noted that user functionality would be improved by the use of Visual Basic within the UIM. The main purpose of the database is to provide a mechanism for material and supplier identification and selection.

The User Interface Module:

The UIM consists of an input stage and an output stage. The input stage receives and controls the search criteria as entered by the user and comprises of three main input stages; search type, search criteria and search results. In search type the user defines the type of search to be carried out, Quick or Detailed, by selecting options from the menu (Figure 8-21).

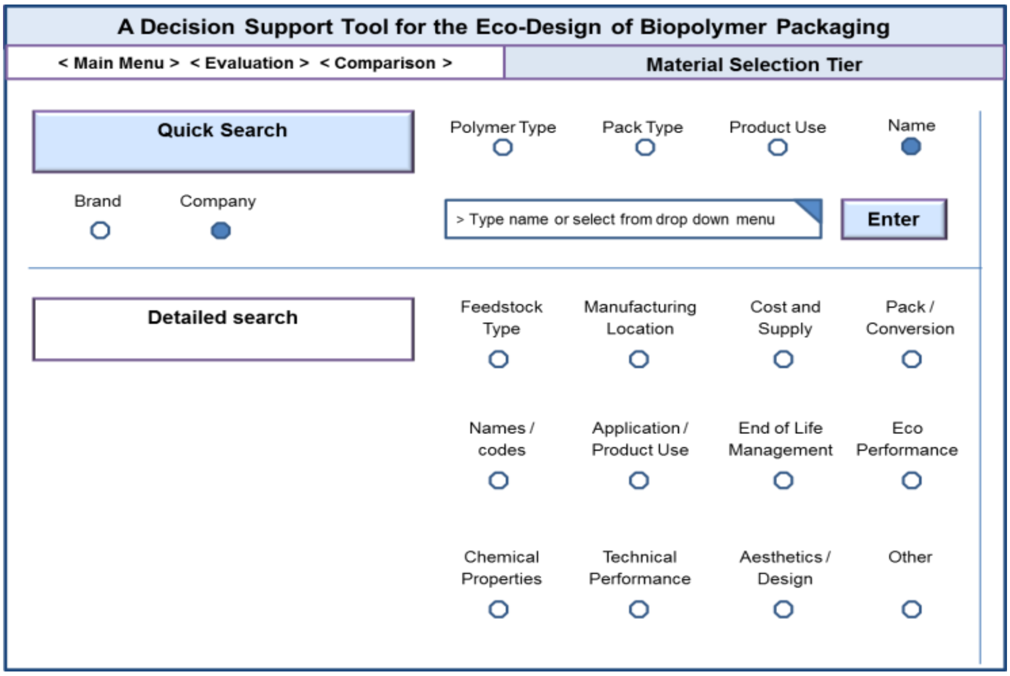
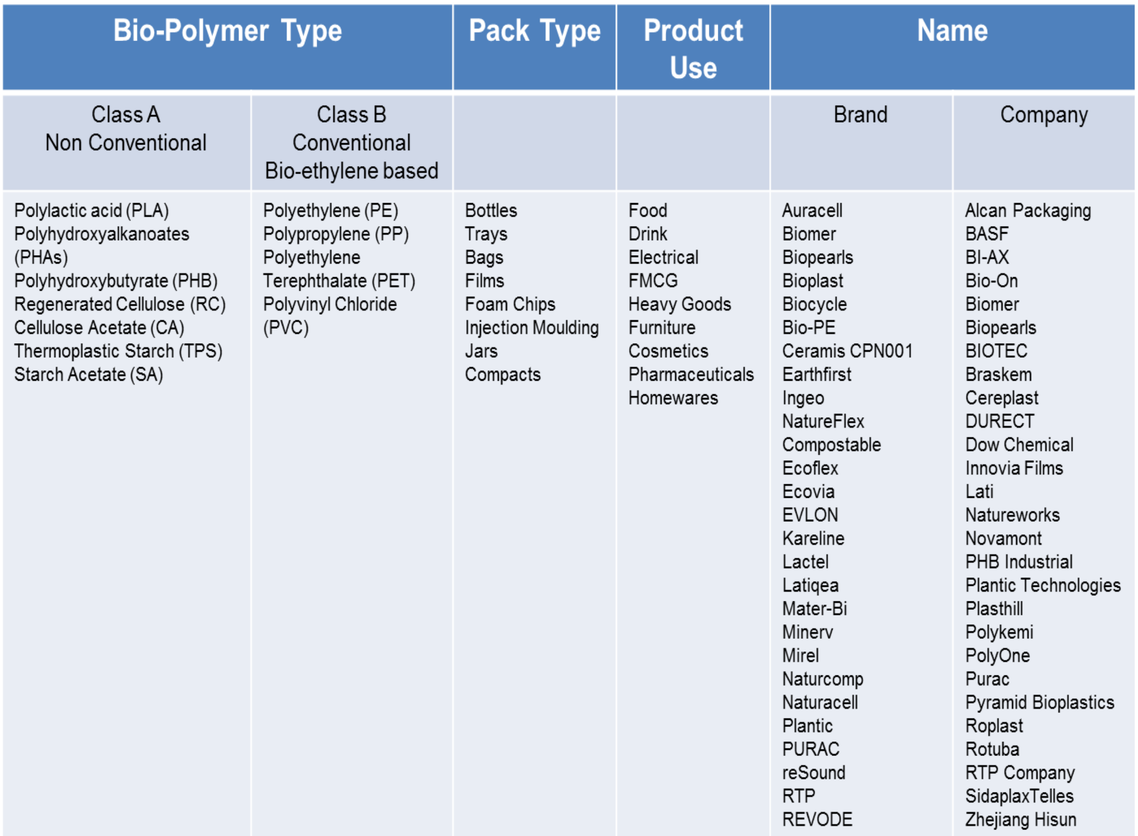


Figure 8-21: Search menu for the user interface module of CASPPa Tier 2.

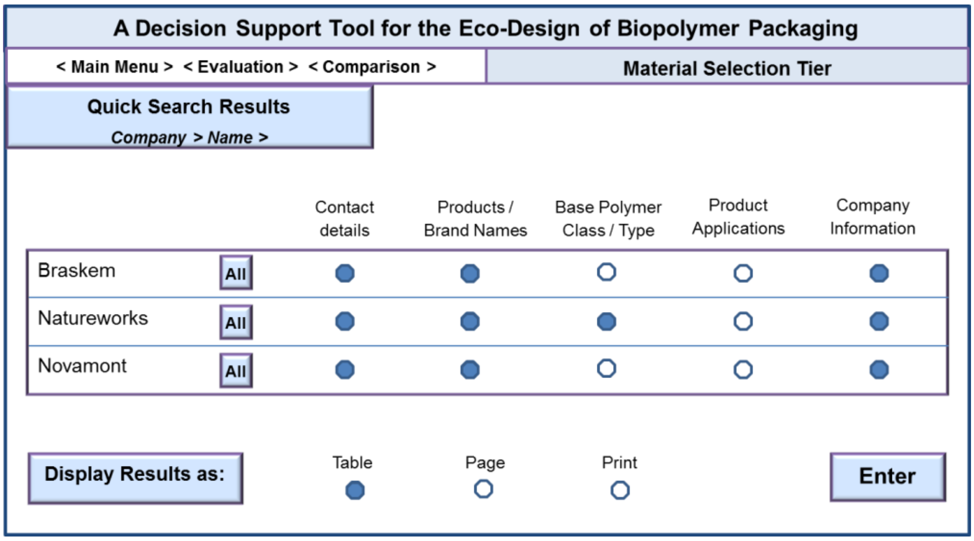
If a Quick search selected, then the user will select 1 of the 4 the search criteria; Polymer Type, Pack Type, Product Use or Name. Once the research criteria have been selected, the user is presented with the option of entering a name or selecting from a drop down menu. In the example shown in Figure 8.21 for the 'Name' criteria, a sub criteria of 'Brand' or 'Company' must first be selected.

The drop down menu contains all the unique fields available for the selectable criteria. Within each drop down menu the user is able to select single or multiple fields. Figure 8-22 shows the different unique fields available for each criteria selection. For the example in Figure 8-21, where the criteria 'Name>Company' was selected, three companies were chosen. These companies are then displayed in the output selection menu, shown in Figure 8-23, at which point the user can select which additional information should be included in the results.



Bio-Polymer Type		Pack Type	Product Use	Name	
Class A Non Conventional	Class B Conventional Bio-ethylene based			Brand	Company
Polylactic acid (PLA) Polyhydroxyalkanoates (PHAs) Polyhydroxybutyrate (PHB) Regenerated Cellulose (RC) Cellulose Acetate (CA) Thermoplastic Starch (TPS) Starch Acetate (SA)	Polyethylene (PE) Polypropylene (PP) Polyethylene Terephthalate (PET) Polyvinyl Chloride (PVC)	Bottles Trays Bags Films Foam Chips Injection Moulding Jars Compacts	Food Drink Electrical FMCG Heavy Goods Furniture Cosmetics Pharmaceuticals Homewares	Auracell Biomer Biopearls Bioplast Biocycle Bio-PE Ceramis CPN001 Earthfirst Ingeo NatureFlex Compostable Ecoflex Ecovia EVLON Kareline Lactel Latiqea Mater-Bi Minerv Mirel Naturcomp Naturacell Plantic PURAC reSound RTP REVODE	Alcan Packaging BASF BI-AX Bio-On Biomer Biopearls BIOTEC Braskem Cereplast DURECT Dow Chemical Innovia Films Lati Natureworks Novamont PHB Industrial Plantic Technologies Plasthill Polykemi PolyOne Purac Pyramid Bioplastics Roplast Rotuba RTP Company SidaplaxTelles Zhejiang Hisun

Figure 8-22: Drop down menus for the Database Quick Search Criteria.



		Contact details	Products / Brand Names	Base Polymer Class / Type	Product Applications	Company Information
Braskem	All	●	●	○	○	●
Natureworks	All	●	●	●	○	●
Novamont	All	●	●	○	○	●

Display Results as: Table ● Page ○ Print ○

Figure 8-23: Output Selection Menu for 'Quick Search' – CASPPa Tier2

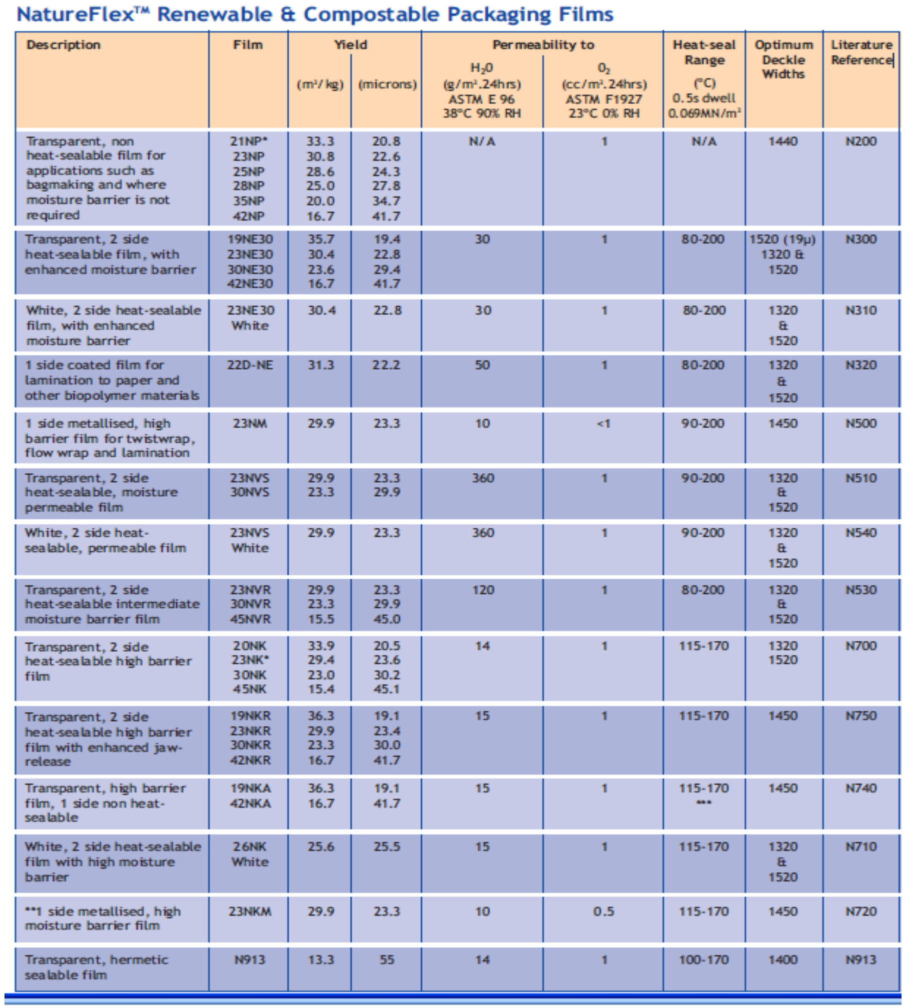
The Data Module:

The DM for the Tier 2 comprises of a single central database built in Microsoft Access, which allows multiple criteria searches to be undertaken. The information contained in this database has been constructed from a combination of technical data provided by the suppliers of these materials as well as data provided by independent material assessment sources.

A key objective in the construction of this database was the standardization of terminologies and measures used. As can be seen from Figure 8-24, the two specification sheets presented are from different material suppliers, whilst the two materials are not the same, there is significant variability in terms and units used and type of data included. The database uses standard terms and units to create easily comparable data that aids the material selection process.

The Processing Module:

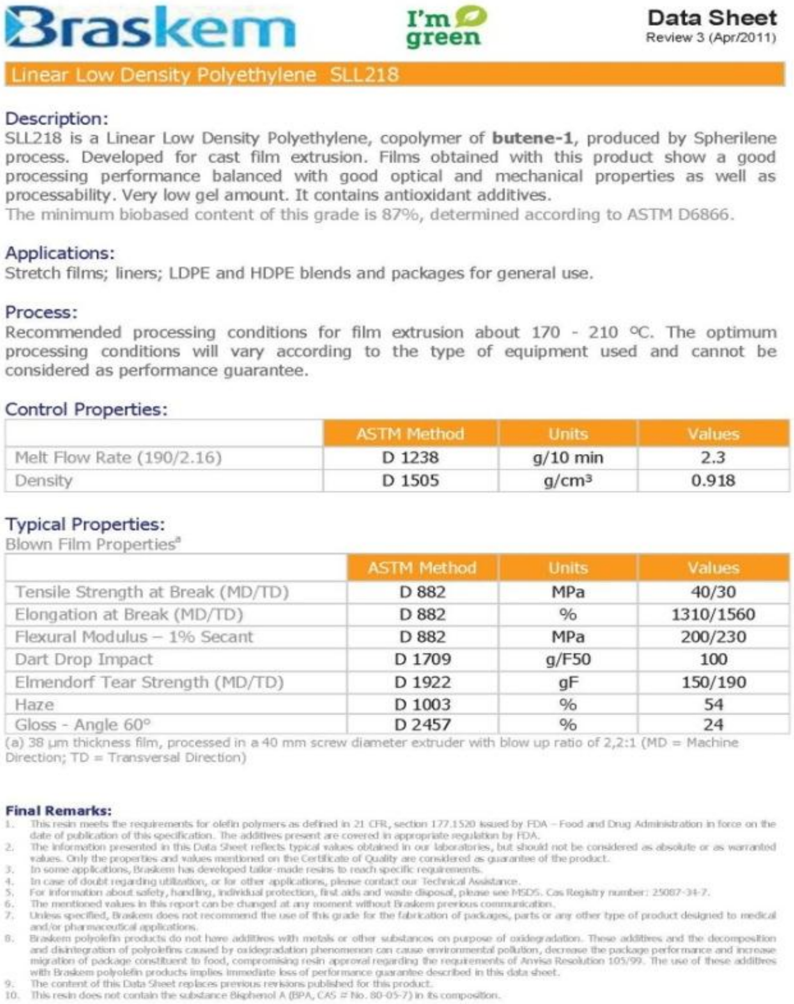
This resides between the database and the user interface. It processes the data from a search into the required output format. This includes production of forms, tables, graphs and data sheets. The Processing module utilizes many of the existing Microsoft Access functionalities, with visual basic providing the mechanism for tailoring the various user interfaces.



NatureFlex™ Renewable & Compostable Packaging Films

Description	Film	Yield		Permeability to		Heat-seal Range	Optimum Deckle Widths	Literature Reference
		(m²/kg)	(microns)	H_20 (g/m².24hrs) ASTM E 96 38°C 90% RH	0_2 (cc/m².24hrs) ASTM F1927 23°C 0% RH	(°C) 0.5s dwell 0.069MN/m²		
Transparent, non heat-sealable film for applications such as bagmaking and where moisture barrier is not required	21NP* 23NP 25NP 28NP 35NP 42NP	33.3 30.8 28.6 25.0 20.0 16.7	20.8 22.6 24.3 27.8 34.7 41.7	N/A	1	N/A	1440	N200
Transparent, 2 side heat-sealable film, with enhanced moisture barrier	19NE30 23NE30 30NE30 42NE30	35.7 30.4 23.6 16.7	19.4 22.8 29.4 41.7	30	1	80-200	1520 (19µ) 1320 & 1520	N300
White, 2 side heat-sealable film, with enhanced moisture barrier	23NE30 White	30.4	22.8	30	1	80-200	1320 & 1520	N310
1 side coated film for lamination to paper and other biopolymer materials	22D-NE	31.3	22.2	50	1	80-200	1320 & 1520	N320
1 side metallised, high barrier film for twistwrap, flow wrap and lamination	23NM	29.9	23.3	10	<1	90-200	1450	N500
Transparent, 2 side heat-sealable, moisture permeable film	23NVS 30NVS	29.9 23.3	23.3 29.9	360	1	90-200	1320 & 1520	N510
White, 2 side heat-sealable, permeable film	23NVS White	29.9	23.3	360	1	90-200	1320 & 1520	N540
Transparent, 2 side heat-sealable intermediate moisture barrier film	23NVR 30NVR 45NVR	29.9 23.3 15.5	23.3 29.9 45.0	120	1	80-200	1320 & 1520	N530
Transparent, 2 side heat-sealable high barrier film	20NK 23NK* 30NK 45NK	33.9 29.4 23.0 15.4	20.5 23.6 30.2 45.1	14	1	115-170	1320 1520	N700
Transparent, 2 side heat-sealable high barrier film with enhanced jaw-release	19NKR 23NKR 30NKR 42NKR	36.3 29.9 23.3 16.7	19.1 23.4 30.0 41.7	15	1	115-170	1450	N750
Transparent, high barrier film, 1 side non heat-sealable	19NKA 42NKA	36.3 16.7	19.1 41.7	15	1	115-170 ***	1450	N740
White, 2 side heat-sealable film with high moisture barrier	26NK White	25.6	25.5	15	1	115-170	1320 & 1520	N710
**1 side metallised, high moisture barrier film	23NKM	29.9	23.3	10	0.5	115-170	1450	N720
Transparent, hermetic sealable film	N913	13.3	55	14	1	100-170	1400	N913

a) Natureflex film from Natureworks Plc



Braskem

I'm green

Data Sheet
Review 3 (Apr/2011)

Linear Low Density Polyethylene SLL218

Description:

SLL218 is a Linear Low Density Polyethylene, copolymer of **butene-1**, produced by Spherilene process. Developed for cast film extrusion. Films obtained with this product show a good processing performance balanced with good optical and mechanical properties as well as processability. Very low gel amount. It contains antioxidant additives.

The minimum biobased content of this grade is 87%, determined according to ASTM D6866.

Applications:

Stretch films; liners; LDPE and HDPE blends and packages for general use.

Process:

Recommended processing conditions for film extrusion about 170 - 210 °C. The optimum processing conditions will vary according to the type of equipment used and cannot be considered as performance guarantee.

Control Properties:

	ASTM Method	Units	Values
Melt Flow Rate (190/2.16)	D 1238	g/10 min	2.3
Density	D 1505	g/cm³	0.918

Typical Properties:

Blown Film Properties[a]

	ASTM Method	Units	Values
Tensile Strength at Break (MD/TD)	D 882	MPa	40/30
Elongation at Break (MD/TD)	D 882	%	1310/1560
Flexural Modulus – 1% Secant	D 882	MPa	200/230
Dart Drop Impact	D 1709	g/F50	100
Elmendorf Tear Strength (MD/TD)	D 1922	gF	150/190
Haze	D 1003	%	54
Gloss - Angle 60°	D 2457	%	24

(a) 38 µm thickness film, processed in a 40 mm screw diameter extruder with blow up ratio of 2,2:1 (MD = Machine Direction; TD = Transversal Direction)

Final Remarks:

1. This resin meets the requirements for olefin polymers as defined in 21 CFR, section 177.1520 issued by FDA – Food and Drug Administration in force on the date of publication of this specification. The additives present are covered in appropriate regulation by FDA.
2. The information presented in this Data Sheet reflects typical values obtained in our laboratories, but should not be considered as absolute or as warranted values. Only the properties and values mentioned on the Certificate of Quality are considered as guarantee of the product.
3. In some applications, Braskem has developed tailor-made resins to reach specific requirements.
4. In case of doubt regarding utilization, or for other applications, please contact our Technical Assistance.
5. For information about safety, handling, individual protection, first aids and waste disposal, please see MSDS. Cas Registry number: 25087-34-7.
6. The mentioned values in this report can be changed at any moment without Braskem previous communication.
7. Unless specified, Braskem does not recommend the use of this grade for the fabrication of packages, parts or any other type of product designed to medical and/or pharmaceutical applications.
8. Braskem polyolefin products do not have additives with metals or other substances on purpose of oxidegradation. These additives and the decomposition and disintegration of polyolefins caused by oxidegradation phenomenon can cause environmental pollution, decrease the package performance and increase migration of package constituent to food, compromising resin approval regarding the requirements of Anvisa Resolution 105/99. The use of these additives with Braskem polyolefin products implies immediate loss of performance guarantee described in this data sheet.
9. The content of this Data Sheet replaces previous revisions published for this product.
10. This resin does not contain the substance Bisphenol A (BPA, CAS # No. 80-05-7) in its composition.

b) Bio-PE Film from Braskem

Figure 8-24: Data Sheets from different Biopolymer Manufacturers

8.5 CASPPa Tier 3: Design Direction

The purpose of the CASPPa design support tool is to support the use of biopolymers for packaging applications where environmental benefits can be achieved over the use of conventional polymers and ensure that the original design intent is maintained through the design process. Most product manufacturing organisations will already have a process of evaluating packaging concepts as part of their own internal development procedures. Once selected, the concepts would go through an additional development and testing phase including production, market and distribution trials. The support offered during Tier 3, is shown in Figure 8-9: Tier 3- Design direction of the CASPPa Design Support Tool. As can be seen there are three key decision stages: Concept Evaluation, Pack Evaluation and Market Evaluation.

During the concept evaluation stage, usually only indicative data is required e.g. price ranges, rating bands. Tier 3 provides a mechanism for evaluating the concepts against the original strategic requirements in addition to the additional evaluation required by the companies own internal processes, thereby providing a mechanism for ensuring the strategic integrity of the design process and concepts selected. In the evaluation of the final pack design a greater detail of information is required. The tool supports the addition of further and more detailed information into the database as it becomes available. This can then be used, with other company evaluation data, to support the final pack selection process. Once the pack has been launched, the market evaluation step of Tier 3 provides useful performance feedback, in particular on those key strategic elements, which can be linked with the company’s financial performance, to provide feedback as to the impact of the strategic objectives identified in Tier 1. The structure for this Tier is now discussed.

8.5.1 *Outline Structure and Content for Tier 3 of the CASPPa Tool*

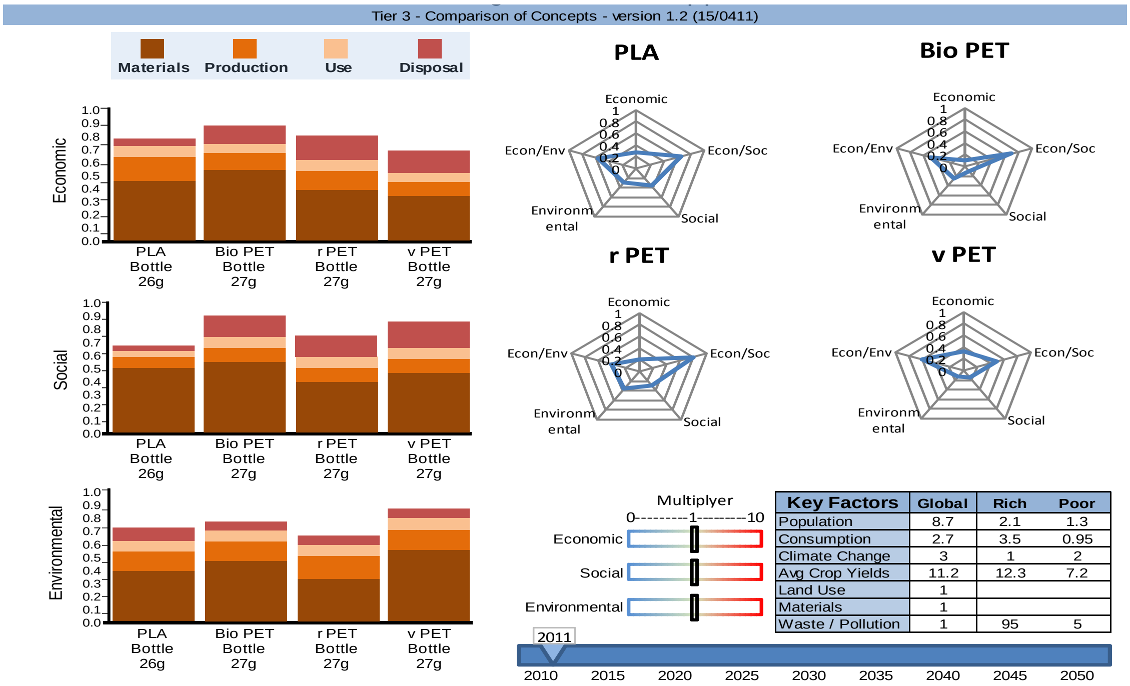
The Comparison Tier (Tier 3) consists of three modules: a User Interface Module (UIM), a Data Module (DM) and a Processing Module (PM). The prototype for this Tier was constructed using Microsoft Excel.

The User Interface Module: This consists of an input stage and an output stage. The input stage receives the details of the materials or pack concepts to be compared. For the material comparison data can be imported from the database module. For the pack concept comparison, the details of the pack concept will need to be input by the user. It is possible that the inputting of information will be done centrally, however the tool allows for multiple users to enter information into the same file. The user interface gathers information on each lifecycle stage of the pack concepts manufacture, use and disposal. The output module displays the information according to the user requirements. Figure 8-25 shows how the environmental impacts of the different pack concepts might be displayed.

The Data Module: For the Tier 3 this consists of a single central database system, the company database(s) and external database(s), as shown in 25, can feed information into CASPPa database but are not part of the CASPPa tool. The central systems database stores the data input by the users as well as a variety of technical, operational, financial and environmental data entered into the system. Other data that is required but which is not held in the CASPPa system should be accessed manually and through the external database(s) or company database(s) as required and imported into the CASPPa database if required.

The CASPPa database contains detailed technical information on the biopolymers from the Tier two data, as well as financial, logistics, purchasing, production, retailer and consumer information for the pack concepts. The data is held in the central shared area of the database or the project area for each concept. Project area data is not automatically updated and is input through the user interface as part of the concept assessment.

The Processing Module: For Tier 3 this is potentially much more complex than in Tiers 1 & 2 if it is to provide fully functional LCA support. However, a number of commercial tools are available, many of which are likely to already be in use. Therefore the comparison of different pack concepts is restricted mainly to the strategic criteria identified in Tier 1 which include Technical, Economic, Environmental and Social impacts. These would form part of the selection process along with the company’s own evaluation processes.


Tier 3 - Comparison of Concepts - version 1.2 (15/0411)

Key Factors	Global	Rich	Poor
Population	8.7	2.1	1.3
Consumption	2.7	3.5	0.95
Climate Change	3	1	2
Avg Crop Yields	11.2	12.3	7.2
Land Use	1		
Materials	1		
Waste / Pollution	1	95	5

Figure 8-25: Output of processing module showing graphic representation options for multiple pack concept comparisons and weighting forecasting option

The information returned by the comparison module as shown in figure 8-25, has three key elements. The first is a simple bar chart comparison based against a single point score. The charts, as presented in Figure 8-26, shows each of the packs being assessed against the original strategic requirements specified in the original sPDS (Output of Tier 1). These results are presented in a single chart where the packs can be easily compared against each other. A separate chart is produced for each of the three key sustainability categories (Economic, Environmental and Social).

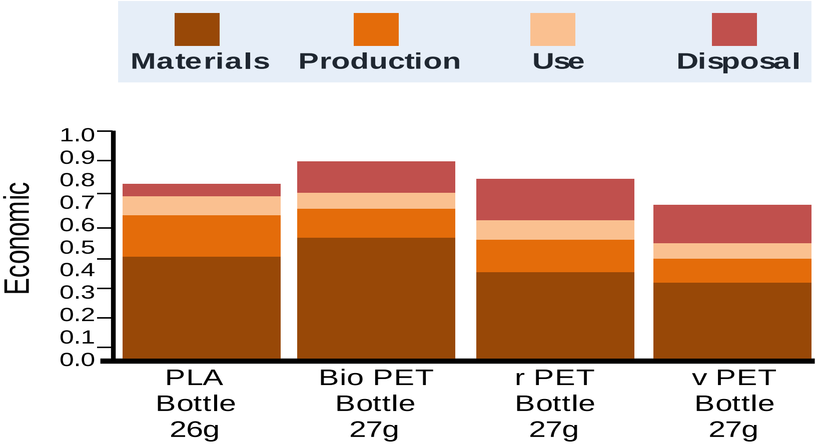


Figure 8-26: Sample of The Bar Chart output for Economic Sustainability

The second method of presenting the data from the assessment against the original strategic objectives as defined in the sPDS. Here the data is presented in the form of a spider diagram, where a separate diagram is produced for each pack, as shown in figure 8-25, and the three key impacts of Economic, Environmental and Social are compared. A further two categories of Economic/Environmental and Economic/Social are included to represent the relationship of the social and environmental impacts to the original economic strategy as developed during Tier 1 and presented in the strategy map. (Figure 8-20). This reinforces the importance of how sustainability factors of social and environmental support the achievement of the businesses core economic strategic goals.

Finally figure 8-28 shows the proposed weighting mechanism that allows user to increase or decrease the weighting applied to each of the factors being assessed (water use, land use etc.), that make up the single point impact score. This enables the user to tailor the assessment to their own business needs and reflect the importance of those factors that matter most to their operation.

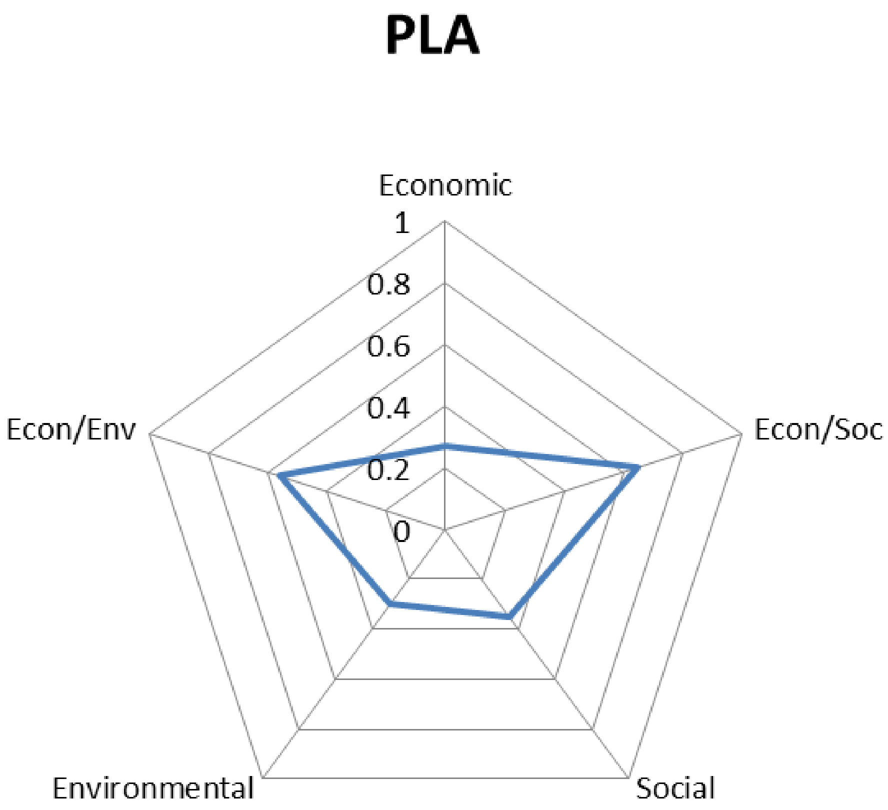
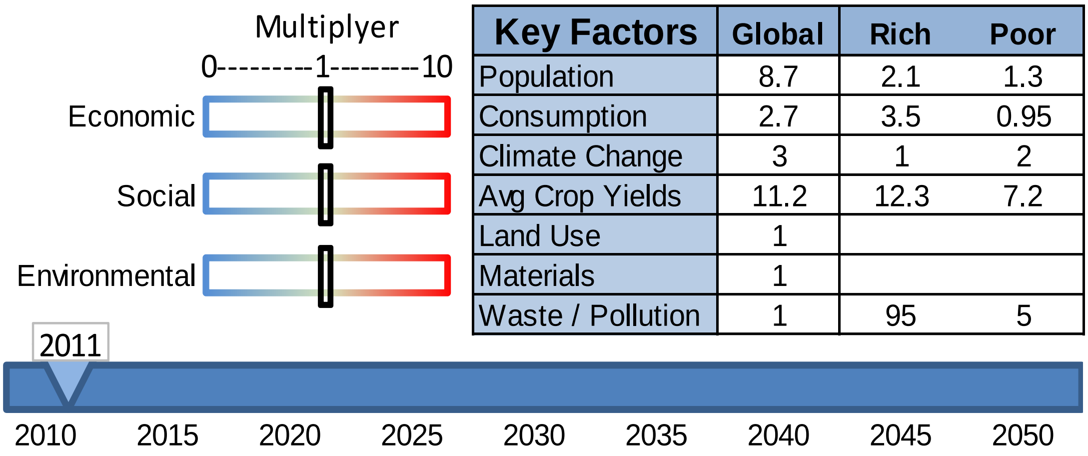


Figure 8-27: Spider diagram showing performance of the PLA pack option against 5 key sustainability strategic objectives.



Key Factors	Global	Rich	Poor
Population	8.7	2.1	1.3
Consumption	2.7	3.5	0.95
Climate Change	3	1	2
Avg Crop Yields	11.2	12.3	7.2
Land Use	1		
Materials	1		
Waste / Pollution	1	95	5

Figure 8-28: Proposed Weighting and Forecasting Mechanism

The sliding bar at the bottom of figure 8-28 is intended to provide a forecasting feature that allows the user to see the change in impacts based on future predictions. Here factors that can be predicted to reasonable levels of accuracy, such as population growth, resource consumption, and technological advances, such as use of non-food feed-stocks, are used to adjust future impacts and provide a rough measure of likely future performance for each pack option. This is important for companies when investing in new technologies and equipment to avoid future redundancy and achieve a minimum payback period. Of course with most predictions, the further forward they are, the less accurate the generally become. It is envisaged that the degree of uncertainty with regard to the forecasting be represented graphically within the results, through the use of a colour scale.

8.6 Chapter Summary

This chapter has described a prototype of a computer aided sustainable design support tool for biopolymer packaging called CASPPa , which has been developed to support the application of the eco-packaging design framework as well as the sustainability assessment methodologies devised in this research. Each of the three tiers that link together to form the CASPPa design support tool, providing decision support at specific stages during the design process have been described. Furthermore, the key steps within each Tier have been described. Tier one utilises a modified SBSC process, a specification and prioritisation process and feasibility evaluation using AHP. The second Tier is based on the use of the CASPPa database which comprises of three modules, namely the interface module, data module and processing module, through which the key objective of Tier 2 are achieved, namely the identification and selection of suitable biopolymer materials and suppliers. The third and final Tier, demonstrated how the tool provided support during the design and development stages, providing support during the concept selection and pack selection ensuring the design intent was reinforced during the design process.

It is believed that the utilization of the CASPPa tool during the packaging design process will ensure the appropriate and most sustainable use of biopolymers to the benefit of the company, the environment and society. Furthermore it will avoid the inappropriate use of biopolymers in packaging, ‘green-washing’, which could have reverse effect, damaging the business environment etc. and potentially stalling the uptake and development of these bio-materials.

The next chapter of this thesis provides two case studies which aim to exemplify the use of the CASPPa tool and how two similar products and pack formats can result in very different biopolymer choices due to the fundamental differences of the business and its corporate strategy.

Chapter 9 Case Studies

9.1 Introduction

This chapter discusses two case studies that have been used to demonstrate the applicability of research concepts related to the SPDF and associated CASPPa design support tool described within this thesis. The chapter begins by providing an overview of these two case studies, both of which focus on the replacement of a conventional PET 500ml bottle with a similar sized biopolymer based one. The first case study is based on an international mega-corporation and its globally branded, carbonated beverage product, such as Coca-Cola or PepsiCo type business/product. The second case study is based on a national SME and its locally branded, non-carbonated mineral water product, such as Belu or Biota.

9.2 Description of the Case Studies

Due to the sensitive and confidential nature of the type of information used in this process, fictitious companies were devised from multiple information sources obtained from a range of companies that matched the case study profiles. By combining this information it was possible to base the case study on real world data, without pertaining to represent or require the involvement of a ‘real-world’ company (due to inherent delays in publishing data). Once a profile has been developed with available relevant real world data, any additional information required will be generated as part of the simulation process. Using the CASPPa design support tool, each of the two scenarios will be evaluated, and the results will be compared to similar ‘real-world’ examples to examine and explore the differences and similarities. The key issues that will be addressed by these case studies are:

- To demonstrate the practical use of the CASPPa design support tool
- To compare the outcome of two contrasting scenarios for a comparable pack.
- To evidence the effectiveness of the tool in meeting the original research aims and objectives.

9.2.1 *Case Study A – Global Carbonated Beverages Plc.*

Global Carbonated Beverages plc. (GCB) is a multinational, mega-corporation with a diverse portfolio of brands and commercial interests. It is a brand leader in multiple product categories, one of which being its flagstone carbonated beverage where it has over 50% of the market share, world-wide. The product sells in a multiple of pack formats, including a range of PET bottle sizes.

The information used in this case study has been amalgamated from publications of companies with similar profiles to that of our subject, GCB plc. Where information required for the study was unavailable, simulated data was used. The ‘real’ data obtained from published literature, relevant to this case study is presented in Table 9-1. Extracts from the key data sources used in this table have been included in Appendix 8.

Table 9-1: GCB plc. Company Facts with ‘Real-World’ Comparisons. Sources: (PepsiCo Inc, 2012a), (PepsiCo Inc 2012b, 2012) (Coca-Cola Enterprises Ltd, 2012), (The Coca-Cola Company, 2013a), (Satistic Brain, 2012).

Company Information	GCB plc	Coca-Cola	PepsiCo
Established	1910	1892 Incorporated 1919	1893 PepsiCo 1965
Sales 2012	$50,000M	$48,017M	$65,492
Profit 2012	$10,000M	$28,964	$10,844
Markets	Global	Global	Global
HQ	Boston, USA	Atlanta, USA	NY,USA
Corporate Slogan 2012/13	Leading by Example	Share a Coke and share the value	Performance with Purpose
Product, Packaging and Sustainability			
Litres of cola sold in 2012	1,000 Billion	1,200 Billion	Estimate 700 Billion
Litres Sold in PET bottles	50 Billion	72 Billion PA (C. 60%)	Estimate 40 Billion
Packaging Slogans	Reach-Refresh-Recycle	“Give it Back”	“creating a better tomorrow than today”
CSR reporting	Annually	Annually	Annually
Recovery Rate (Pack equivalents)	2012 = 45% Target 2015 = 51%	2009 = 35% Target 2015 = 50%	Varies by market and product - Over 10%
Use of recycled PET in bottles	2012 = 20% Target 2015 = 25%	2012 = 25% Target 2015 = 25%	2012 = 5-10% (US) Ideal = 100%
Reduce	Light-weighting	Light-weighting	Light-weighting
Factory Waste	Zero waste to landfill	Zero waste to landfill	Zero waste to landfill
Other	Social projects	Social projects	Social projects

9.2.1.1 GCB plc. Company Strategy

As with the majority of publicly listed companies, GCB plc's primary commitments is to its shareholders through dividends (profits) and growth (share price). This focus on shareholder value will therefore be at the core of its corporate strategy. Lazonick and O'Sullivan in their paper "Maximising shareholder value: a new ideology for corporate governance" state that there is a "widespread belief in the economic benefits of the maximization of shareholder value as a principle of corporate governance" (Lazonick & O'Sullivan, 2000). Whilst this might be the guiding principle and ultimate metric of the corporate strategy, it could be achieved in many different ways and over varying timescales. A good corporate strategy should provide direction as well as goals and be understandable to all levels within an organisation. To achieve this, particular variations of the corporate strategy will often be developed according to need, as described in Johnson, Scholes and Whittington's book 'Exploring Corporate Strategy: Text and Cases'. The corporate-level-strategy is generally concerned with the structure and scope of the organisation and how its resources will be distributed. Business-level-strategies are concerned more with how each strategic business unit (SBU) should compete in their markets, and Operational strategies are concerned with how to effectively deliver these first two goals (Johnson, et al., 2008). For this first case study a corporate strategy and a packaging strategy have been developed which encompasses the business and the operational strategy, but begins with a public mission and vision statement.

9.2.1.2 GCB plc. Mission and Vision

Corporate Slogan: Leading by Example

Mission Statement: To build a better world where investors, partners, employees, customers and communities can prosper and where our consumers can live healthy and happy lives.

Company Vision: To lead responsibly, grow sustainably, perform outstandingly and refresh completely. Where our investors can prosper with pride and our customers consume with confidence.

9.2.1.3 GCB plc. Global Corporate Strategy

In line with its vision and mission statements the corporation's primary focus is on 'doing better'. As the established market leader, it competes as much with itself as with its competitors, always striving to improve. GCB plc. aims to be an inspirational leader as well as the market leader. So, in addition to excellence in financial, market and business performance, the company understands that to be sustainable, it must also excel environmentally and socially. Its slogan, ‘Leading by Example’ implies that it is prepared to be judged on its behaviour as well as performance.

The company has a matrix structure of both regional operational divisions and global brands. Its flagship brand ‘Loca’ is a carbonated beverage drink that was named the world’s most recognised brand. Whilst different regions have some autonomy over the promotions and pack formats sold, the logo and product formulation is controlled centrally. Innovation is also centrally controlled with two global research and development centres in the USA and UK that work closely together. The R&D budget is second only to the marketing budget in size and is targeted mainly at innovation and scale up. The company will identify new technologies as they immerge and will invest heavily in the right ones to bring them to market first.

The five key global corporate strategic goals and their metrics are:

- **Shareholder value** – An annual growth in share price and dividend of 6%
- **Brand recognition** – To increase the market share of the core brands by value and volume and to add annually to the portfolio of mega brands.
- **Corporate leadership** – To inspire and be inspired, to lead where others will follow and to be excellent, responsible and purposeful in our actions and dealings with others.
- **Business sustainability** – To improve the sustainability of our organisation on each of the three key areas with measurable action – Economic, Environmental and Social.
- **Global innovation** – To bring to market new technologies and process that support the delivery of the four previous goals at a regional and global level

The global corporate strategy has financial performance at its core, but with a clear message from the top that this must be achieved responsibly and innovatively. GCB are leaders not followers and this strategy reflects this purpose.

9.2.1.4 GCB plc. Global Sustainable Packaging Strategy

"To build a better world where investors, partners, employees, customers and communities can prosper and where our consumers can live healthy and happy lives – Leading by Example".

GCB has clearly identified sustainability as one of the five goals of its corporate strategy, which will in part be delivered by the fifth goal innovation. Sustainability and innovation are central to the modern packaging industry and to GCB's packaging strategy. For GCB packaging is not begrudgingly accepted as a necessary evil but embraced as an opportunity to add value to the business, brand and consumer experience. For GCB, the packaging of its flagship product is as important to the brand as the product itself and is a primary focus on meeting its sustainability goals. As such the title reflects the importance of sustainability to the packaging strategy.

GCB is committed to packaging that:

- Supports growth and shareholder value
- Reflects the core product and brand values of Superiority, Quality and Taste.
- Improves our competitiveness through optimal cost and performance
- Provides protection for our product and brand investments
- Is innovative, smart and impactful.
- Minimises GCB's environmental and social footprints

GCB's Sustainable Packaging Aspirations

- Use packaging that is 100% recyclable
- Increase the use of recycled content in packaging.
- Reduce unnecessary material/packaging use and waste
- Avoid negative social and environmental impacts
- Be cost competitive with alternative materials/formats
- Reduce GCB's carbon footprint

GCB's Packaging Development Principles

- Ethical, sustainable and feasible
- Be Innovative: Improve-Invest-Invent
- Use scientific principles and methods
- Deliver real measurable benefits and improvements
- Be responsible and impartial in balancing multiple considerations
- Consider short and long term solutions – evolution / revolution

9.2.1.5 GCB plc, Technical and Operational Data

The following section provides additional technical and operational data on GCB, for decision making and design specification activities within the case study.

9.2.1.5.1 Product

Loca: GCB's flagship carbonated 'cola' beverage drink containing water, sugars and artificial sweeteners, caramel, acetic and phosphoric acid, and flavourings. It is therefore acidic, with an average pH of 2.5. The shelf life of the PET bottled product depending on the particular formulation, ranges from 12 to 24 weeks. Assume a minimum of 12 weeks shelf life is required with a maximum acceptable CO_2 loss of 30%. The following chart (Figure 9.1) shows CO_2 loss for a typical 1.5 litre PET bottle of carbonated beverage (Composite Agency, 2013).

9.2.1.5.2 Production

The product is produced by GCB as a concentrate which is then sold to licensed bottlers world-wide. The licenses give the bottlers exclusive rights to supply a particular territory. These long term contracts provide enable the bottlers to take a long term view in their businesses and invest in state of the art equipment to maximise productivity and reduce waste. The equipment used will vary by bottler, but they are usually high speed, fully automated lines, with the PET bottles being produced direct from resin or from injection moulded pre-forms in-line, in continuous 'blow fill' process (Cirillo, 2012).

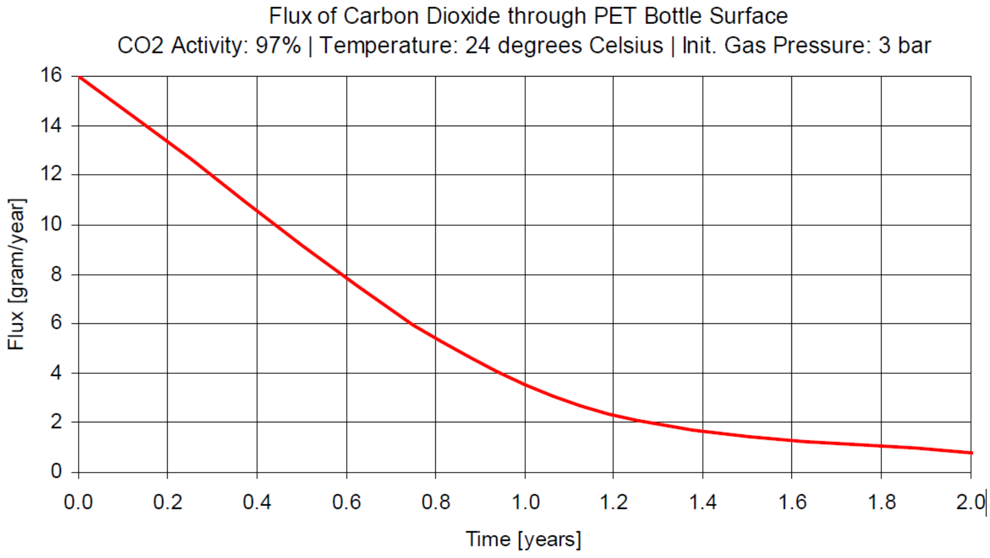


Figure 9-1: CO_2 loss over time, expressed in flux. Source:(Composite Agency, 2013)

Assume GMB’s bottling lines run at speeds of up to 1000/ppm. This compares with the Coca-Cola plant in Baton Rouge, LA, “The “12- and 20-oz and 0.5-L PET bottles of both sparkling beverages and Dasani water at speeds to 800/min” (Mohan, 2011). With the investments made in high speed, automated packing and filling lines, it is reasonable to assume that there would be great reluctance and significant financial constraints on changes that would impact their efficiencies or productivity.

At the end of the filling lines, the 200mm tall bottles are automatically shrink-wrapped into packs of 24, and palletised on standard pallets 8 layers high, then Stretch-wrapped and transported to the warehouse.

9.2.1.5.3 Storage and Distribution

A standard pallet, with an 8 layer stack of 500ml PET bottle, will have dimensions of 1200x1000x1800mm and weigh approximately 1 metric ton. The pallets are stored in racking 1 pallet high or on the floor two pallets high, giving the load on a single bottle, assuming even weight distribution, of between 3.5kg to 8kg.

During distribution, with weight shift, vibration and shock, loading on individual bottles has been recorded at peaks significantly higher than this. Distribution methods are predominantly road based but can vary dramatically in terms of road quality and vehicle type. From palletised loads in large lorries to mix individual cases in vans with distances ranging from 1 to 1000+ miles. Temperatures can also range from minus 15 to plus 60 degrees centigrade.

Following implementation of the current light-weighted 500ml 24g PET bottle recorded damage levels remained unchanged. During extensive distribution trials on further weight reduction, a lower weight bottle of 22g gave rise to higher failure weights under more extreme conditions. This would indicate that current packs performance is close to optimal and would require shape modification to enable further weight reduction.

9.2.1.5.4 Sales

The bulk of products are sold mainly through large retailers, although sales of individual bottles chilled and ready to drink from smaller retailers, filling stations, cafes and vending machines is increasing rapidly and a key market (65%) for this format.

9.2.1.5.5 Consumption and Disposal

The 500ml bottle is re-closable and whilst intended to be consumed by a single individual, consumer research has shown that consumer who chosse this format over others, such as the 330ml can, do so for this feature and will generally consume the product in stages over a period of 1-2 hours. The ability to carry the bottle safely once it has been opened without leaking, breaking etc. is essential.

Although the bottle is 100% recyclable, and significant investment has been made to encourage consumers to recycle, the majority of bottles still end up in municipal waste and will require sorting and separation. The recycling rate therefore depends on local waste facilities and varies significantly by region and country.

9.2.2 *Case Study B – National Mineral Water Ltd*

National Mineral Water (NMW) Ltd. is a national, SME with a single product portfolio of still mineral water. Whilst not a brand leader, it is well known regionally and uses a percentage of its profits in local/regional social and environmental projects. The product sells in 3 PET bottle sizes formats of which the 500ml is the biggest seller.

The information used in this case study has been amalgamated from publicly available information on companies with similar profiles to that of the fictitious NMW ltd. Where information required for the study was unavailable from either of these companies, simulated data ‘based on general market trends’ was used. The data obtained from published literature, relevant to this case study, is presented in Table 9-2. Extracts from the key data sources used to compile this table are included in Appendix 8.

SMEs or Small to Medium size Enterprises (SMEs) have, by definition, a smaller pool of resources to draw on. Often this access to resources plays a key factor in the decision making process at both a strategic and operational level. Recognition of the importance of resources at the SME level led to the development of *resource-based theory* and its suitability as a methodology for owners and executives of SMEs (Rangone, 1999). The model proposed by Rangone suggests that an SME’s competitive advantage is based on one or more of three basic capabilities: Innovation, Production and/or Market Management, and asserts that an “SME explicitly or implicitly, consciously or unconsciously, puts its strategic focus on one or more of the above basic capabilities.”

Table 9-2: NMW Ltd. Company Facts with 'Real-World' comparisons. Sources: (BIOTA Brands of America, Inc, 2013); (Holstrom, 2004); (Belu, 2013); (Hurley, 2012); (Article 13, 2013).

Company Information	**NMW Ltd**	**Belu**	**Biota**
Founded	2004	2004	C.2004
Annual Sales	£2.5M (2012)	£2.4M (2012)	Est.c.$1M (2005/6)
Profit 2012	£200k	Donated £134k	Est. Break Even
Markets	Regional UK	Regional (UK)	National (USA)
HQ	Brighton	London	Colorado
Guiding Principle	Message in a Bottle (Social, Environment)	"A better way to do business." (Ethics)	"Making a difference. One bottle at a time." (Environment)
Product, Packaging and Sustainability			
Litres of water sold p/a	2M (2012)	Est. 2-4M (2012)	Est. 1M (2005/6)
Litres Sold in PET bottles	2M (2012) 100%	Est. 1-2M (2012) Assume 50%	Est. 1M (2005/6) Assume 100%
Slogans	Beach Beautiful	"Belu. Made with mineral water and ethics."	"America's Premium Spring Water."
CSR reporting	In Annual Report	Online	Online
Recovery Rate (Pack equivalents)	UK Average 40%+	UK Est. over 40%	N/A
Use of recycled PET in bottles	2012 = 25%	2012 = 50%	N/A
Reduce	Light-weighted 500ml bottle 16gm	Light-weighted 500ml bottle 16gm	N/A
Factory Waste	Zero waste to landfill	No Data	N/A
Other	Social projects	Social projects	biodegradable

9.2.2.1 NMW Ltd. Company Strategy

During the last decade a number of new companies have been founded on a set of principles that extended, beyond just the supply of services or products, to their role in society and the positive changes they can make. These companies were established to make a better world first and a better product second, often using profits to undertake charitable work (Belu, 2013). However to deliver on these founding principles required the business to be successful; financially, competitively and operationally and so led to the development of a strategy that encompassed the radical and traditional aspects of the business values.

For this second case study a business and packaging strategy have been developed which encompasses both the founding principles (Social and Environmental) and an innovation capability approach. The business model for NMW is a social enterprise (Not for Profit Organisation) combined with an innovation culture start-up.

9.2.2.2 NMW Ltd. Mission and Vision

Guiding Principle**:** “Message in a bottle” (Social and environmental)
Mission Statement**:** To leave our world a better place than when we founded it.
Company Vision: To combine healthy consumption with ethical production to leave our customers, society and environment ‘Beach Beautiful’.

9.2.2.3 NMW Ltd. Company Strategy

NMW started with a single guiding principle – that it could not only change the bottled water market but fundamentally how companies do business; for the better. This simple philosophy is captured in its company slogan “message in a bottle” which embodies the principle that, through their bottle water, they are not just informing the public that there is a better way to consume bottled water, but showing industry that there is a better way to run a business to benefit society as well as its shareholders. The message in NMW’s bottle is ‘ethical capitalism’ which, with its head office in Brighton, makes an obvious marine connection that has both positive (hope) and negative (litter) connotations.

In addition to its social and environmental benefits, the company also want to promote the health benefits of drinking water. This vision is captured in its slogan “beach beautiful”, which has both health and environmental significance.

The five key company strategic goals and their metrics are:

- **Ethical Capitalism** – To maximise growth and profits without compromising our ethical principles of fair trade and sustainable production. In addition to growth targets of a 12% increase in sales and 6% increase in margins, the company has committed to spending £100k or 50% of profits (whichever is the greater) on social and environmental projects.
- **Environment** – To minimise its own environmental impacts by locally sourcing and minimising its products environmental footprint. The company aims to remain carbon neutral through its charitable projects. Independently assessed by external consultants annually.

- **Health** – To promote the health benefits of drinking water and ensure that its water is enjoyed at the highest levels of purity, quality and freshness. Measured on market sampling and consumer feedback.
- **Community** – To be an active member of the local community in which it is based, supporting and encouraging a strong community spirit and positive action. Measured on the number of community projects and benefits achieved.
- **Innovation** – To be innovative in every aspect of its business, using fresh thinking and new technologies to challenge the status quo and deliver on its promises.

Whilst NMW ltd. has ethics and sustainability at its core, there is a clear recognition that only from a position of financial health, can it make good on its promises.

9.2.2.4 NMW Ltd. Packaging Strategy

"To combine healthy consumption with ethical production to leave our customers, society and environment 'Beach Beautiful." Mission Statement 2012

NMW Ltd. has clearly identified that its business ethics must also be based within business realism. However this is not at odds with sustainability which clearly identifies economic sustainability as one of the three core pillars along with society and the environment, or as otherwise known as the three P's: People – Profit and Planet. It also includes innovation as one of its key strengths and a means by which it might reach its other strategic objectives. Packaging is one area it can demonstrate its commitment to its environmental and innovation principles. Not constrained by brand history or manufacturing capability, it has a blank page from which to investigate all options in order to deliver the best possible solution. For NMW, the choice of packaging will be a test of its commitment to its core principles.

NMW is committed to packaging that:

- minimises its environmental and social impacts
- is healthy, safe and fit for purpose
- demonstrates fresh thinking
- is cost effective and good value
- meets its customers' expectations

NMW's Sustainable Packaging Aspirations:

- Use packaging that is natural and pure
- That does not damage the environment
- Reduces GHG emissions
- Is competitive with alternative options
- Avoids negative social impacts
- Reduce production and consumer waste

NMW packaging development principles:

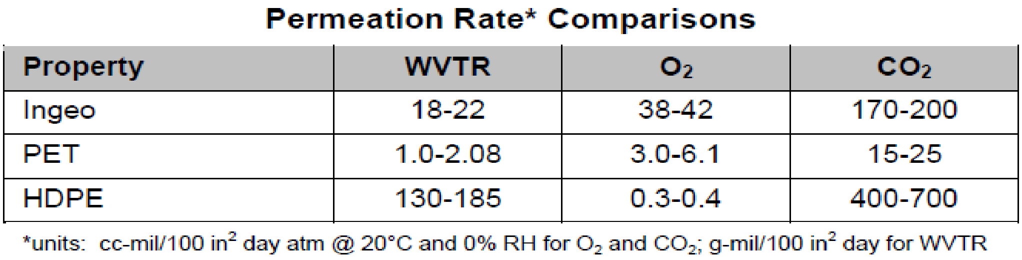
- Ethical, Sustainable and Feasible
- Use natural, local materials
- Be innovative and bold
- Lead not follow
- Function over form

9.2.2.5 NMW Ltd., Technical and Operational Data

The following section provides additional technical and operational data on NMW, for decision making and design specification activities within the case study.

9.2.2.5.1 Product

Life: NMW's still mineral water contains just natural spring water filtered from chalk hills. It therefore has a very slightly alkaline pH of 7.5. The shelf life of the PET bottled product is given as 6 months, however properly stored it can be significantly longer. Assume a minimum of 6 months shelf life is thought to be required with a maximum acceptable product loss therefore of 5% or 25ml over 6 months at standard room temperature/humidity, based on its Water Vapour Transmission Rate (WVTR), as shown in Figure 9-2.



Permeation Rate* Comparisons

Property	WVTR	O_2	CO_2
Ingeo	18-22	38-42	170-200
PET	1.0-2.08	3.0-6.1	15-25
HDPE	130-185	0.3-0.4	400-700

*units: cc-mil/100 in^2 day atm @ 20°C and 0% RH for O_2 and CO_2; g-mil/100 in^2 day for WVTR

Figure 9-2: Permeation rates of different polymers. Source: (NatureWorks LLC, 2011)

9.2.2.5.2 Production

The water is bottled by NMW at source using pre blown PET bottles. The company is investigating buying pre-forms and investing in a 'blow fill' line but needs to justify the investment cost. As such the company is still very flexible in terms of its pack formats but this flexibility could be lost once it makes a commitment to upgrade its production.

Bottles are shrink-wrapped in trays of 12.

9.2.2.5.3 Warehouse and Distribution

The company uses a local third party warehousing and distribution service and therefore has only a minimal consolidation area outside its production. It uses standard pallets 1200x1000mm and stacks the product 6 layers high giving a height of approximately 1300mm. The pallets are stacked two high, giving the load on a single bottle, assuming even weight distribution, of around 5kg. Distribution is mainly local, using small lorries or vans, over short distances. Any damage due mainly to poor handling i.e. dropping.

9.2.2.5.4 Sales

The bulk of sales are mainly through local independent retailers, restaurants and forecourts. The company is currently negotiating with large multiple to stock product in its local stores.

9.2.2.5.5 Consumption and Disposal

Consumption times vary from minutes to days and there is also an element of re-filling (re-use). The bottle is 100% recyclable and recycling is encouraged, primarily by using a quantity of recycled PET in the bottle

9.3 A Comparison of Two CASPPa Case Studies

The selection of the two different companies with similar product and pack formats; non-alcoholic drinks in PET bottles, provides an opportunity within the case study to show the influence of the company's strategy, rather than that of the product e.g. (comparing a rigid drinks package with a flexible snack pack), on the pack design process. To emphasise this further, the two case studies are presented in parallel, enabling comparisons to be made at every stage of the process. The data tables for the two company presented earlier in this chapter (Tables 9-1 and 922) are summarised in Table 9-3 allowing two companies to be compared.

Table 9-3: Comparison of company data for the two case studies.

Company Information	GCB Plc.	Company Information	NMW Ltd
Established	1910	**Founded**	2004
Sales 2012	$50,000M	**Annual Sales**	£2.5M (2012)
Profit 2012	$10,000M	**Profit 2012**	£200k
Markets	Global	**Markets**	Regional UK
HQ	Boston, USA	**HQ**	Brighton
Corporate Slogan 2012/13	Leading by Example	**Guiding Principle**	Message in a Bottle (Social, Environment)
Product, Packaging and Sustainability			
Litres of cola sold in 2012	1,000 Billion	**Litres of water sold p/a**	2M (2012)
Litres Sold in PET bottles	50 Billion	**Litres Sold in PET bottles**	2M (2012) 100%
Packaging Slogans	Reach-Refresh-Recycle	**Slogans**	Beach Beautiful
CSR reporting	Annually	**CSR reporting**	In Annual Report
Recovery Rate (Pack equivalents)	2012 = 45% Target 2015 = 51%	**Recovery Rate (Pack equivalents)**	UK Average 40%+
Use of recycled PET in bottles	2012 = 20% Target 2015 = 25%	**Use of recycled PET in bottles**	2012 = 25%
Reduce	Light-weighting	**Reduce**	Light-weighted 500ml bottle 16gm
Factory Waste	Zero waste to landfill	**Factory Waste**	Zero waste to landfill
Other	Social projects	**Other**	Social projects

Sections 9.3.1 – 9.3.3 will demonstrate the application of each of the three Tiers of the CASPPa tool, using the two simulated companies (GCB Plc. and NMW Ltd) and the two product profiles developed and described in the previous sections.

In order to simulate the ‘group’ based activities during the case study and to reduce the possibility of bias, selected individuals, with the appropriate knowledge and skills were allocated to play the role of CEO, Marketing, Sales and Manufacturing Managers/Directors, Engineers, Designers etc., as determined by the Tier/Step requirements. During the decision making process, the ‘actor’ playing a specific role must base their decisions on the data provided in the company profiles Section 9.2, however where not pre-specified, the actor may improvise based on their knowledge and experience and will record the assumptions that were made on which influenced the decision.

9.3.1 *CASPPa Tier 1: Strategic Direction*

The first step for each company is to establish the scope of the exercise, the results of this are summarised in figure 9.3.

9.3.1.1 Scope

GCB has a complex matrix business structure that means the central packaging development function must communicate separately with regions and brands. To minimise the complication during development it was decided to restrict these to the core brand in one region. Due to unit cost issues, the proposition most likely to support the additional cost and benefit from the sustainable credentials is the 500ml bottle variant.

NMW has a much less complicated business structure and would lose the benefits of economy of scale in having two variants of the same size. It will launch the pack over the whole range but restrict it initially to one size variant. Likewise, NMW feels that the 500ml variant would be the most appropriate format to launch with.

9.3.1.2 Business Exposure from Defined Scope

The next step is to consider the financial, technical environmental and social exposures. Both companies recognise the possible financial implications of using biopolymer packaging in terms of increased unit costs and possible technical issues regarding performance, shelf life and product quality. However, GCB is much more risk averse due to the complexity of its business and the difficulty in being able to test every possible supply chain scenario. NMW are mostly concerned with product taint issues.

Project Scope	
GCB Plc.	**NMW Ltd.**
Core Brand Cola only 2 variants – diet and original	All brands
Restricted geographic region e.g. Northern Europe	All regions
PET 500ml bottle size only	500ml PET bottle launch

Figure 9-3: Project scopes for the two case studies

For the environmental and social exposure both companies are aware of the issues with the current packaging and recognise the need to improve. Using the Sustainable packaging checklist the two companies develop their key exposure concerns using the forms described in chapter 8.3.4.3 and 8.3.4.4. These are summarised in table 9.4. The lagging and leading indicator tables for both companies are as per those described in Chapter 8 and provided in Table 8-5 and Table 8-6.

9.3.1.3 Perspectives

The next stage of the process is to develop the 5 perspectives as per figure 8.10. The first of these is shown below in figure 9.5.

The financial perspectives reflect the different business models. GMB Plc., like any other Plc. has share-holder value as a top priority. To reflect this it choses profit as the top financial measure which it aims to increase by 25% over three years. It intends to achieve this by increasing its market share and margins as outlined in Figure 9.5.

NMW sees this project more in terms of meeting its overall philosophy of ethical production. As such its TFM would be a return on investment of 6% per annum, which would be achieved mainly through increased sales.

Business Exposure from Packaging	
GCB Plc.	**NMW Ltd.**
Financial	**Financial**
• Business efficiencies • Sales and returns	• Unit cost • Investment cost
Technical	**Technical**
• Shelf life • Performance and compatibility	• Taint • Use
Environmental	**Environmental**
• Recyclability • Carbon Footprint - GHG	• Litter • Resource use
Social	**Social**
• Food competing	• Land and water competing

Figure 9-4: Financial, Technical, Environmental and Social Exposure

Financial Perspectives	
Measures and Lagging Indicators	
GCB Plc.	**NMW Ltd.**
TFM **Increase profits by 25% over 3 years.**	**TFM** **Return on investment (ROI) 6% pa**
Achieved by:	**Achieved by:**
Increase in market share to 60%	Increase Turnover by 10% pa
Whilst improving margins by 2-3%	Increase Unit Sales by 25%

Figure 9-5: Financial perspectives for the two case studies

The remainder of the four perspectives are considered according to the process described in chapter 8, and the resulting strategy map and strategic design specification is produced by each company. As can be seen from figure 9.6, the key environmental strategy for GCB is on the recycling of packaging whilst from figure 9.7 it is clear that for NMW it is the reduction of litter and the use of natural, renewable resources.

Strategic Packaging Design Specification for GCB Plc.			
Perspective	**Considerations**	**Specification**	**Importance**
Financial	• Profit Increase 25%		• High
Customer	• Quality • Environmentally and socially responsible.	• No tainting or loss of product quality • Recyclable, renewable and sustainable	• High • Medium
Internal Process	• Material cost • Production • Efficiency • Shelf Life	• Maximum 12% increase • Compatible with existing systems • No loss of efficiency • No loss of shelf life	• Low • Medium • High • High
Learning & growth	• Employee satisfaction	• Efficiency targets met • Innovation	• High • Medium
Non-market Environmental	• Waste • Resource depletion	• Recyclable • Renewable	• High • Medium
Non-market Social	• Food availability • Non Hazardous	• Non-food grade raw materials • Non Hazardous	• Medium • High

Figure 9-6: Strategic Packaging Design Specification for GCB Plc.

Strategic Packaging Design Specification for NMW Ltd.

Perspective	Considerations	Specification	Importance
Financial	• ROI 6%		• High
Customer	• Quality • Environmentally and socially responsible.	• Healthy - no taint or chemicals • Sustainable – Bio friendly	• High • Medium
Internal Process	• Material cost • Shelf Life • Distribution	• Maximum 12% increase • No loss of shelf life • Fit for purpose – no damage	• Medium • High • Low
Learning & growth	• Employee satisfaction	• Feel good about company / product • Ethical and progressive	• Medium • High
Non-market Environmental	• Waste • Resource depletion	• Biodegradable – no litter • Renewable	• High • Medium
Non-market Social	• Food availability • Worker rights	• Non-food competing • Ethical, fair trade	• Medium • High

Figure 9-7: Strategic Packaging Design Specification for NMW Ltd.

9.3.1.4 Strategic Feasibility and Material Selection

Having generated the strategic design specifications the results were compared against the feasibility database. For GCB, none of the materials met all the criteria however in terms of meeting the high priority criteria, the key material group were the bio-conventionals. Progressing this to material selection identified no suitable commercial biopolymer being available; however the key supplier of bio-ethylene was highlighted. As PE is used in the production of PET, the material the company required for its packaging to meet the strategic requirements, it decided to explore the development of a new bio-polymer to match its current PET.

NMW was able to match most of its requirements. Concerns over the confidence factor regarding the non-food competing aspects of the bio-polymers. The company decided not to proceed with the development of a bio-polymer pack until greater certainty could be established on the bio-degradability of the material and more importantly, the feed-stocks used to manufacture the biopolymer. In the short term the company decided to use recycled glass bottles which were returnable. This result was in-line with the course of action taken by similar companies with the exception that NMW did not proceed whilst others did and then reverted back to a recycled plastic or glass bottle.

9.4 Case Study Summary

This case study has demonstrated the application of the CASPPa tool using two simulated case study based on data obtained from companies with similar corporate profiles. The study focuses primarily on the initial stages of the design process, using Tier 1 and 2 of the CASSPa tool. Whilst it would be obvious to most manufacturers that the selection of packaging materials and design of the pack would be greatly influenced by the requirements of the product and production processes, and that for those with a creative or marketing background how branding and target consumer market would also influence the design of the pack, what would be less clear is how the 'soft' factors that originate from the corporate sustainability strategy might influence the choices made during the design process and the potential impact that this could have on the final pack choices.

The results from this case study demonstrate how the 'soft' factors originating from the corporate and business strategy can be translated into 'hard' design attributes that can be expressed as technical and commercial performance requirements within a packaging design specification. The case study showed how, based on two very similar pack formats and product types, the variations in sustainability strategy and corporate culture can lead to the development and selection of two very different results regarding the adoption of biopolymer and their application within a new pack design. This clearly highlights the wider range of factors that must be considered during the sustainable pack design process and the importance of ensuring that at the range and complexity of considerations increase as the process progresses, the original strategic requirements that initiated the consideration of biopolymers is not lost or unduly diluted in the final result. Furthermore, the importance of reflecting on the project outcomes and the performance of the pack in the marketplace with regard to these initial requirements should not be forgotten and must be used to improve and influence the company's future sustainability strategy.

Chapter 10 Concluding Discussions

10.1 Introduction

The discussions provided by this chapter bring together the major issues examined by this research and summarises the research contributions. The concluding discussions are based on the broad headings identified as the research scope in Chapter 2, highlighting the key findings and knowledge gained from the research.

10.2 Research contributions

The author has identified the following as the important contributions made by this research in the area of biopolymer packaging:

i. Highlighting potentially significant shortcomings in current biopolymer ‘packaging’ life cycle assessment, which has acted as a barrier to wider scale adoption of these materials in packaging applications.

ii. Extending the scope of existing knowledge on biopolymers to demonstrate that these materials can play a key role in achieving a sustainable future for plastic packaging applications, but their inappropriate use can lead to serious negative business and environmental consequences.

iii. Definition of a novel approach for supporting the design of biopolymer packaging based on specific strategic objectives, material performance specification and pack/product design requirements.

iv. Development of a comprehensive sustainable packaging design framework and associated computer aided decision support tool to ensure the use of biopolymers in packaging is directed towards the most appropriate applications and applied in the most effective manner.

v. The wide range of factors (including technical, operational, commercial, environmental, marketing, branding, etc.) influencing the appropriate selection of biopolymer materials for a particular application has been demonstrated through the case studies presented in this thesis.

10.3 Concluding Discussion

The following subsections draw together and discuss the results of the main research activities, and use the research scope to structure the evaluation of research.

10.3.1 *A review of biopolymers and biopolymer based packaging*

An extensive literature review carried out as part of this research has identified a rapidly expanding range of biopolymer materials that have many potential commercial applications, one of which being for packaging. Largely due to their natural bio-origins, there is a presumption that the use of these materials, as a replacement to conventional polymers, will always lead to an environmental benefit and improve a product and/or a company's overall sustainable performance. However the reality, as shown by this research and other published work in this area, is significantly more ambiguous and controversial. For example, the results of LCA studies have indicated a number of negative impacts of biopolymers that can occur across the life cycle of the packaging, which may include changes in land use, eutrophication, loss of production efficiency, increased wastage and the reduction in quality of conventional polymers recovered and recycled from current waste streams.

The wide range of available biopolymers have resulted in commercial examples of their use for most pack types (flexible, semi-rigid and rigid packaging), with varying levels of success. Coca-Cola launched a new bottle called the 'Plant' Bottle which contained both biopolymers and recycled conventional polymers. Due to the selection of a biopolymer (bio-PET) that was 100% compatible with its existing polymer (PET), it was able to make a direct substitution without impacting the performance of its products or production processes. The only impact to the business was financial, which was probably recovered through the positive press of being first to market with a 'bio-PET' bottle. The success of this is indicated by the company's continued expansion of its use and the development of a 100% bio-PET version. A less successful application of a biopolymer was Pepsico’s use of the biopolymer PLA in a crisp packet for its ‘Sunchips’ products. This was quickly withdrawn following customer complaints about it being “too noisy”. These examples indicate the importance of selecting the appropriate biopolymer with the right properties for a particular application and the need for detailed information and support for companies and packaging designers in doing so.

Concerns have also been raised regarding the negative impacts that wide scale adoption of biopolymers might have on global food production capacity, reducing the future availability and affordability of food, particularly in poorer nations. In the short term biopolymers will continue to compete directly or indirectly with food production, however it can be argued that continued growth in their use will also fund commercial research and investment in new technologies and feed-stocks to reduce this conflict. Furthermore, it could also be argued that the use of biomass for biopolymer production, which is potentially recoverable and reusable at end-of-life, is more advantageous than the use of biomass for fuel, which cannot be recovered and for which alternative options using renewable energy technologies exist (e.g. solar, wind, wave).

Biodegradability was initially seen and promoted as the main benefit of biopolymers. This has now been challenged through national and international directives restricting biodegradable materials going to landfill. It is also argued that biodegradation would be the least efficient end-of-life management option for biopolymers in the waste hierarchy, due to the significant loss of resources used in its original production. On the other hand these non-conventional, biodegradable biopolymers can contaminate existing conventional polymer recycling streams significantly reducing the quality and usefulness of the recycled polymer. These conflicting considerations make a clear case that even though the current use of biopolymers is relatively small, the consequences of their inappropriate use can be quite significant.

10.3.2 *A review of Life Cycle Assessments of biopolymers.*

The review of life cycle studies undertaken in this research has highlighted that the detailed, high quality, primary data needed for conducting a comprehensive LCA of biopolymer packaging is generally not available. This is mainly due to the confidentiality surrounding the production processes, and the general complexity and subjectivity of selecting representative ‘use’ and ‘end-of-life’ scenarios. Furthermore where real primary data is available, the degree of impartiality associated to it is often questionable. Therefore, it is asserted that the existing LCA studies on biopolymers do not provide clear guidance or understanding as to the true impacts of biopolymer packaging use.

One of the other challenges which make it very difficult to produce repeatable and comparable LCA studies is the variability of feed-stocks used in the production of biopolymers. From one batch to the next a biopolymer’s environmental impacts can vary dramatically according to the variety of crop, the farming method used, crop yield and quality and distance from plant. This introduces additional complexity and subjectivity that the majority of existing eco-design tools and methods are not able to support.

Whilst in commercial literature there is wide concern regarding the potential impacts that biofuels and biopolymers on food availability and affordability, particularly in developing countries, no studies were found that looked at the social impacts of biopolymers in great detail. Furthermore, the use of land has also been linked with potential issues of population displacement and the use of ‘forced’ labour. This would indicate a clear need for including social impacts in the assessment of biopolymers, even at a very basic level.

These inconsistencies in results from existing LCA studies point to a significant difference between the current impacts and potential future impacts of conventional polymers and biopolymers. In this context, there is a need for design support capable of predicting future impacts, as most companies will be interested in the long term impacts of biopolymers as well as the present ones.

10.3.3 *Investigation of commercial biopolymer packaging applications and the drivers and barriers to wider scale adoption.*

A key barrier to biopolymer adoption is the security and stability of supply due to the scale and immaturity of the sector. This is particularly true in food packaging applications where margins are tight and the pack can be a significant part of the total SKU cost. In such cases, it is clearly important for manufacturers committing to a long term contract, to avoid any potential for price shocks. Many of the companies supplying biopolymer packaging do not have the financial strength to make these commitments, particularly when the feed stock prices are so erratic. Additionally the small scale of the biopolymer market reduces the number of suppliers, so reducing competition and the ability to dual source.

Biopolymer development has evolved from a focus on biodegradable materials such as PLA and TPS (which are not compatible with conventional polymers) to a greater focus on the polymers bio-origins. This has advantage over biopolymers such as bio-PET, which are compatible with conventional polymers. This diversity of biopolymer development has created some confusion as to what constitutes a biopolymer. In addition, the initial growth of biopolymer adoption was driven largely by a perceived consumer demand for more sustainable and environmentally friendly packaging. However, at present the public enthusiasm for biopolymers is less than might be expected partly due to the negative press on biopolymer packaging failures (e.g. Sunchips, Biota) and contradictory LCA reports. This highlights a need for greater clarity and managing business expectations as to what biopolymer packaging can achieve in terms of their long term sustainability goals.

10.3.4 *Assessment of commercial packaging eco-design tools.*

The majority of existing eco-design tools are intended for use in the latter stages of the design process. This limits their scope to impact the design direction at an early stage where generally the greatest benefits can be achieved at the lowest cost. Furthermore, the mainstream eco-design tools, such as SimaPro, GaBi and CES Eco Selector, are not optimised for packaging design use and the more niche tools that do support this (e.g. COMPASS and PIQET) lack the functionality and usability of mainstream products. More notably, none of the tools reviewed offered sufficient design support for the effective selection and use of biopolymer in packaging design.

In addition, the current eco-design tools do not support the translation and communication of strategic aims and objectives into measurable actions such as design attributes and material specifications. This is important as the main driver for using biopolymer packaging is usually a strategic one that is not directly attributable to the company’s core financial goals. The proposed design framework and tool presented in this thesis, links the core and non-core strategic goals and provides a mechanism to communicate and validate these at each stage of the design process, to ensure the final pack design meets the original strategic intent.

10.3.5 *Development of a sustainable design framework for biopolymer packaging*

In the initial stage of this research, it became apparent that there was not a single method or tool that could be used to capture the strategic intention, assess this against material properties and provide appropriate design support for their inclusion in the new packaging. This highlighted the need for a stepwise approach to take advantage of the benefits offered by a number of methods and tools to achieve the desired research objectives, thus a framework consisting of a number of stages was developed by this research.

In applying this framework it also became evident that there was a large amount of data that needed to be processed and a number of consecutive steps that needed to be performed by different individuals at various stages of the design process. This highlighted the need for a computer aided support tool to help implement the various stages of the framework. The author claims that this design framework, whilst intended for packaging applications, it could offer further opportunities to improve the use of biopolymers across a range of product applications.

10.3.6 *Realisation of a sustainable design support tool for biopolymer packaging.*

In prototyping the CASPPa sustainable design tool, the intention has been to avoid duplication with existing tools and processes already in widespread use within companies. In addition, where feasible, existing tools and methods were selected and then modified to focus the functionality on biopolymer packaging application. One example of this was the adoption of the BSC methodology, developed for use at a corporate business level and to adapt it for use in the first Tier of CASPPa.

In order to increase the likelihood of the tool being taken up by industry, it was felt that it needed to be capable of being embedded within the existing corporate packaging design processes and procedures. Therefore, the tool was developed to complement existing tools and provide additional functionality rather than replicate existing support.

Although significant research time and effort has been spent on developing the ideas and framework contained in this thesis, the author fully acknowledges that the CASPPa tool is clearly only a prototype tool to demonstrate the applicability of the research. Clearly its commercial use would require significant investment to enable the development of a fully tested, user friendly, software tool.

10.3.7 *Demonstrate of research applicability through case studies*

For the purposes of validation and demonstration of the research concepts, two case studies were identified as being suitable to demonstrate the effectiveness of the tool. A clear objective of these case studies was to follow a systematic implementation of the sustainable design framework proposed by this thesis, and to show its feasibility and applicability in selecting the most sustainable route for the design of a biopolymer package. The two case studies primarily considered the same pack type, i.e. a 500ml bottle for water/beverage. The major difference was in the type of company and its strategic aims and objectives. The purpose of this was to demonstrate how the strategic intent of the company could influence the choice of biopolymer and how this could be implemented and supported by the CASPPa tool.

10.3.8 *The vision for future biopolymer packaging design*

Plastics packaging has been shown to reduce resource consumption through waste reduction and efficient production. In fact plastic packaging has become an essential enabler for modern ‘urbanised’ societies, a trend which is forecasted to grow globally. It is therefore highly likely that the demand for plastics packaging will continue to grow as without it, our current supply chains could not efficiently function.

Currently, the majority of plastics used in packaging are made from fossil fuels, which is a finite resource. The eventual depletion of these fossil fuels and the continued rapid increase in global demand, points logically to the eventual necessity for an alternative source of polymer materials. This clearly highlights the need for further research to extend our knowledge of biopolymers and their role in future packing applications.

10.4 Limitations of the Research

The research reported in this thesis has investigated an area which is highly complex and diverse in its scope. Research into the sustainable use of renewable materials often generates diametrically opposed views within the academic community. The scope of this research has therefore focused on biopolymers and their use in packaging applications where the author has the greatest knowledge and insights, having spent 20 years as a packaging design consultant.

However, an inherent facet of any research is its limitations due to the time and resources available. Thus a number of the limitations of this research are outlined below.

i. Lack of access to quality data due to the confidentiality surrounding biopolymer production process.
ii. Lack of detailed investigation into the social impacts associated with the land use, production and use of biopolymers.
iii. Lack of inclusion of a detailed study exploring the impacts on the packaging conversion and filling processes for different biopolymers.
iv. Lack of more comprehensive and varied case studies assessing the ease of use of CASPPa in conjunction with existing packaging design tools.
v. Lack of detailed consideration of future legislation and its potential impact on biopolymers.

Chapter 11 Conclusions and Further Work

11.1 Introduction

This chapter identifies the major conclusions drawn from the author's research, and proposes possible avenues for further extension of this work.

11.2 Conclusions from the Research

The conclusions drawn from this research are as follows:

i. Biopolymers clearly have a key role in future packaging applications, but their real potential and environmental benefits are still not fully understood. The research has identified a number barriers to their wide-scale adoption which if addressed could have a significant impact on their rapid uptake.

ii. The review of eco-design methods and tools clearly highlighted a lack of appropriate design support for biopolymer packaging, in particular tools that could be used in the early stage of the design process where major impact could be made at low cost.

iii. Whilst biodegradability was one of the initial drivers for biopolymer adoption, this has recently been challenged, and now the preference is for their recycling and reuse. However the most appropriate EoL options for biopolymers cannot be identified with any degree of certainty, due to the lack of dependable LCA data.

iv. The wide range of competing requirements that must be considered when designing biopolymer packaging highlights the need for a systematic framework that considers not only the technical and commercial requirements but also the higher level strategic sustainability objectives of the business.

v. This research has demonstrated how 'top level' general corporate and business sustainability strategies related to the use of biopolymers can be translated into actionable packaging design specifications, and be effectively communicated at both a tactical and operational level.

vi. The sustainable packaging design decision support tool developed by this research provides a mechanism for continuous assessment of the original sustainability requirements of the business throughout the pack design process, thus ensuring that the final biopolymer packaging meets the initial strategic objectives.

vii. Due to the inherent complexity of organisational structures influencing the packing design processes, any additional design methods or tools specifically tailored to support biopolymers, needs to readily integrate with existing company processes to ensure its commercial adoption.

viii. The case studies presented in this thesis clearly demonstrate that the selection of biopolymers, even for similar products and pack types, can be significantly influenced by other competing company considerations (such as corporate strategy, market distribution, production flexibility etc.) which may result in the selection of very different biopolymer materials.

ix. Packaging will continue to play a vital role in protecting and preserving products in future manufacturing applications. As the demand for sustainable packaging materials continues to increase, so the need to find alternative solutions to deal with the subsequent biopolymer waste will become more urgent.

x. Although the results of this research has advanced the understanding and application of biopolymers in sustainable packaging design, there are clearly a number of additional areas which require further investigation as highlighted in the final section of this chapter.

11.3 Further Work

The author recognises the following areas of work as the most valuable extensions of the current research.

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Appendices

Appendix 1 Conference paper - 2010

Opportunities for Biopolymer Resource Conservation through Closed Loop Recycling.

Appendix 2 Conference paper - 2011

Eco-design tool to support the use of renewable polymers within packaging applications.

Appendix 3 Conference and Journal Paper – 2011/2012

A Holistic Approach to Design Support for Bio-Polymer Based Packaging.

Appendix 4 Journal Paper - 2012

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Appendix 5 Journal Paper - 2012

Bioplastics in the context of competing demands on land.

Appendix 6 Supporting Data for CASPPa

Packaging Design Specification for a plastic bottle

Appendix 7 Supporting Data for CASPPa

Sustainable Plastics Packaging Checklist

Appendix 8 Supporting Data for Case Study

Sample reference and simulation data

Appendix 1

Conference paper - GPEC 2009

Introduction

This paper was presented at the Global Plastics Environmental Conference on Sustainability and Recycling. GPEC 2010, Florida, USA and published in the proceedings the same year.

OPPORTUNITIES FOR BIO-POLYMER RESOURCE CONSERVATION THROUGH CLOSED LOOP RECYCLING

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Abstract

Oil-derived plastics have become well established as a packaging material over the past 75 years due to their many technical and commercial advantages. However, the disposal of plastic packaging waste, a large proportion of which still goes to landfill, continues to raise increasing environmental concerns. Meanwhile, the price of oil continues to rise as demand outstrips supply. In response, biodegradable polymers made from renewable resources have risen to greater prominence, with a variety of materials currently being developed from plant starch, cellulose, sugars and proteins.

Whilst the polymer science continues apace, the real ecological impacts and benefits of these materials remain uncertain. Although life cycle assessment (LCA) has been used to provide comparisons with oil-derived plastics, published studies are often limited in scope, allowing the validity of their conclusions to be challenged. The literature appears to support the popular assumption that the end-of-life management of these materials requires little consideration, since their biodegradable properties provide inherent ecological benefits. Opportunities for conserving resources through the recycling of biopolymers are rarely addressed.

Through a review of current academic, industrial and commercial progress in the field of biopolymers, a number of LCA case studies are proposed which will address this weakness in existing research, related to the recycling of biopolymers. These, or similar, studies are required to provide a more complete picture of the potential effects of a transition from non-renewable to renewable polymers, thus allowing material selection decisions to be made with greater confidence throughout the packaging supply chain.

Introduction

The annual global production capacity of bio-derived polymers, based on company announcements, is forecast to grow from 0.36 Mt (million metric tonnes) in 2007 to 2.33 Mt in 2013, an annual increase of 37 percent. (Shen et al., 2009). In addition, the types of products and brands using bio-derived polymers (BDPs) for their packaging has begun to shift from predominantly niche, unprocessed items such as organic fruit and vegetables, to more mainstream global consumer brands such as cola, crisps and chocolate. The rate and scale of this change has been highlighted through a study of company, press and trade announcements on new products launched in BDP based packaging. The results of this study were then analysed in terms of the number of announcements per year and the general significance of each with regard to the importance of the brand, the size of the company and market and the level of technical performance.

Although there are many factors which have influenced the growth and development of BDPs, the most fundamental of these has been the growing public desire for environmentally friendly and sustainable packaging, and the popularly held belief that bio-derived polymers meet this requirement. To a large degree this view has been fostered both from the claims made by manufacturers, and the obvious emotional attraction towards a material with a natural, renewable pedigree. However, the factors now influencing the adoption of bio-derived polymer have shifted from niche catagory, market driven demand to mainstream political policy, with numerous government initiatives actively promoting and encouraging the procurement of ‘bio-based’ and ‘sustainable’ products.

Whilst well intentioned, the current level of scientific understanding of the environmental benefits achievable from these materials, particularly for certain packaging applications and end of life scenarios, is inadequate or simply non existent. The danger in creating an artificial market for these materials, whilst questions remain about their overall benefits, is that it may force the premature adoption of a particular technology or material, which in turn could hinder the development of more effective and sustainable environmental solutions in the future. It also increases the risk of a consumer backlash if these premature claims are then proven to be false or vacuous.

This paper begins with an overview of the major conventional and bio-derived polymers used in packaging applications, comparing the key types of packaging application and end of life management options. Next the findings from a study on the reported packaging applications of bio-derived polymers for new product launches from 2004 to 2009 are discussed, followed by a review of the major drivers and barriers that have influenced their growth both negatively and positively. The results of a literature review on published LCA studies for both bio-derived and conventional polymers are then discussed. The paper concludes by highlighting the key challenges that must be met to enable the long term sustainable adoption of bio-derived polymers as a mainstream packaging material.

Polymers in Packaging Overview

Packaging uses approximately 37% of the 260 million tones of plastics produced globally each year, (Plastics Europe, 2008), which equates to just over 1% of the world's total crude oil production, the majority of which being 'burnt' as fuel for power generation or transport, (Queiroz & Collares-Queiroz, 2009). However, plastics packaging is highly visible and pervasive, and as a result has become almost symbolic of our modern society's excesses and wastefulness. The reality however is more complex, food waste from farm/factory to shop in Western Europe is 2-3%, compared with 30-50% in developing countries (Incpen, 2009). So it is more often the case, that when used correctly, plastics packaging can actually save energy, being lightweight, rugged, versatile, safe and capable of meeting a range of mixed barrier requirements for longer shelf life and less product waste.

It is however this combination of plastics' durability and packaging's disposability that attracts so much negative press, and has contributed to packaging becoming the first industry to be targeted by specific waste legislation, arising from the EU's Directive 94/62/EC on Packaging and Packaging Waste. Despite the many regulations and initiatives to limit the use of plastics packaging, consumption has continued to grow at an average of 9% annually (Plastics Europe, 2008).

The majority of polymers used in packaging are thermoplastics, this means they can be re-heated and re-formed multiple times, making them suitable for recycling provided they can be separated into their specific polymer types. The most important of these are PE, PP, PVC, PET and PS, which account for 96% by dry weight of polymers used for packaging applications, of which over 70% are used for food and beverage packaging, as shown in Fig 1 (Applied Market Information, 2008)

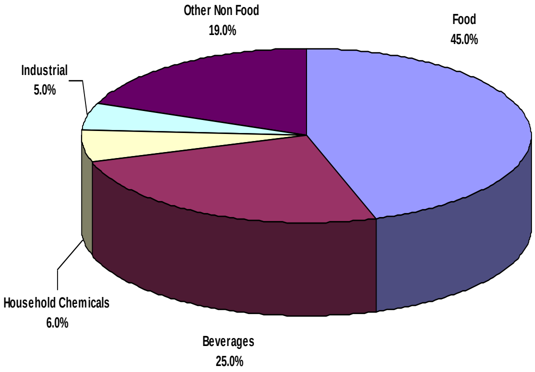

Figure 1 End Use applications for polymer packaging in Europe 2007 – Source data: Applied Market Information

Bio-derived polymers, which have developed both technically and commercially over the past 20 years, are now appearing in mainstream packaging applications. Two distinct routes have begun to emerge; those materials which largely retain the original source material's properties, namely their ability to bio-degrade and / or be compostable, which we will refer to as 'Class A' bio-derived polymers (BDPa), and those that are identical to the current fossil derived polymers, such as PE, PET, PVC, but are produced from a bio-derived intermediate such as bio ethylene. These we will refer to as 'Class B' bio-derived polymers (BDPb). The key fossil-derived (FD) and bio-derived (BD) polymers and their main packaging applications are shown in Table 2.

			Packaging Applications				End-of-Life Management			
Key w wholly applicable p partially applicable - unknown *BE – produced from bio ethylene			Flexibles – films, bags...	Semi Rigid – ThF, SBM - Trays, bottles...	Rigid – Inj. Moulded - caps, devices...	Foamed – Moulded, extruded – Filler, pads...	Compostable - Home	Compostable - Commercial	Bio-degradable	Recyclable
Fossil Derived – Conventional Polymers	**PE**	**Polyethylene**	W	W	W	W				W
	LDPE	Low Density PE	W			P				W
	LLDPE	Linear Low Density PE	W							W
	HDPE	High Density PE	W	W	W	W				W
	PP	**Polypropylene**	W	W	W	W				W
	OPP	Orientated PP	W							W
	BOPP	Biaxially Orientated PP	W							W
	PS	Polystyrene	W	W	W	W				W
	PET	**Polyethylene Terephthalate**	W	W						W
	APET	Amorphous PET	W	W						W
	PETg	PET Glycol		W						W
	CPET	Crystallised PET	W	W	W					W
	OPET	Orientated PET	W							W
	PVC	Polyvinyl Chloride	W	W	W					W
	PA	Polyamide - Nylon	W	P	P					W
	PVA	Polyvinyl Alcohol	W	P			P	P	P	-
Mixed	PVC	Polyvinyl Chloride – BE*	W	W	W					W
	PET	Polyethylene Terephthalate – BE*	W	W						W
	Blends	Starch blends (FD copolymers)	W	W	P	W	P	P	P	
	Blends	PLA blends (FD copolymers)	W	W	P		P	P	P	
	Blends	Conventional FD/BD blends	W	W	P			P	P	
Fully Bio-derived	RC	Regenerated Cellulose	W				P	W	W	W
	CA	Cellulose Acetate	W				P	W	W	W
	PE	Polyethylene – BE	W	W	W	W				W
	PP	Polyproylene – BE	W	W	W	W				W
	TPS	Thermoplastic starch	W	W	P	W	P	W	W	W
	SA	Starch Acetate	W				P	W	W	W
	PLA	Polylactide - Poly Lactic Acid	W	W	W		P	W	W	W
	PHA	Polyhydroxyalkanoates	W	W	W		p	W	W	W

Table 1 – Key packaging polymers and their application and end use characteristics

Applications of Bio-derived polymers

Bio-derived polymers have been used as packaging materials since the 1950s with the development of cellulose film, but were soon supplanted by the 'new' range of fossil derived plastics. However in the 1990s a new wave of bio-polymers emerged, driven by the need for more sustainable and environmentally friendly packaging. The first polymers were made from starch, cellulose and natural oils such as linseed, the technology for which was well known. These were followed by 'second generation' bio-polymers; PLAs, PHAs and PHBs, which could be formed. sealed or moulded using existing packaging equipment. These found application in bottles, trays and clamshell packaging. but were limited by their functional performance and barrier properties. The third and latest generation of bio-polymers to enter the market includes the 'Class B' thermoplastic polymers; PET, PE and PVC. As these polymers are identical to their FD polymer equivalents, they can be mixed together in any proportion with no noticeable difference , enabling the percentages to be adjusted as and when supply and cost demanded. They can also be recycled, mixed with their FD equivalents, with no adverse effects on the reprocessing of or the subsequent re-use of the recyclet.

To understand how the application of bio-derived polymers for packaging has evolved, an online review of published announcements for new product launches in bio-derived packaging was undertaken. This included searching the websites and press archives of all the main biopolymer manufacturers, associated trade press and the key industry bodies, associations and institutes for the environment, packaging and plastics industries, dating back to 2004. It is an expected and an accepted limitation of this review that as a material becomes established, i.e. first generation bio-polymers such as cellulose film and foamed starch chips, they will probably become less noteworthy of comment and so frequency will decline even if use actually increases. Also, the results record launch activity, not ongoing use, and so should not be viewed accumulatively.

From Table 2, we can see that food and drink account for the majority of new pack introductions whilst flexible films and bags are the dominant pack type.

Product Group	Grp Total	Bio-derived Polymers - Materials					Pack Types			
		Cell-ulose	TPS starch	PLA	PHA	BDE PET	Films /Bags	Semi-rigid	Rigid	Foam
Food	**55**	24	6	25	0	0	38	16	1	0
Drink	**12**	2	0	8	0	2	2	0	10	0
Cosmetics	**4**	1	0	2	1	0	1	0	3	0
Distributn	**2**	0	1	1	0	0	1	0	0	1
Other	13	1	6	6	0	0	11	2	0	0
Total	**86**	**28**	**13**	**42**	**1**	**2**	**53**	**18**	**14**	**1**

Table 2 –Product launches by BDP and pack type

This reflects the current use of FD polymers as shown previously in Figure1 and the compatibility of use with food, both in terms of origin and end of life management.

When these new introductions are plotted against their launch dates, the lower graph line in Figure 2, a picture begins to emerge of gradual annual growth in application. However, this only shows the frequency of product launches and does not consider the individual significance of each new introduction in terms of the BDP used. As it is not possible from these announcements alone to ascertain accurate data with regard to the volume of sales, material use, specific barrier properties, transmission rates etc, a simple weighting factor was applied instead. The factor used was allocated based on five easily assessable key criteria: Brand awareness, Company size, Launch market size, Potential market size and Application complexity. A weighting factor was applied for the first four criteria of 1x for local, 3x for national or 5x for global. For the fifth criteria, application complexity, a weighting of 1x for low complexity, 3x for medium (thermoformed/laminated), 5x for high complexity (injection moulded, blown, high barrier). Once applied the sum total was divided by five to a final value of between 1 and 5 for each application.

When this data is re-plotted with the weighting factor it shows a much sharper growth curve (figure 2, top line) particularly during the last two years, that might indicate that BDP's are entering a new accelerated growth phase. This would lead to higher growth than other data has previously suggested, such as BDP production capacity investments, (Shen et al, 2009) which predicts growth by 2020 to reach 3.5 Mt capacity and earlier projections published by Crank et al. (2005) of between 2.5mt and 4.17Mt. In addition, when the two graphs are compared it suggests that in addition to a general increase in use, these new bio-derived polymers are gaining wider market acceptance, moving from niche, synergetic applications such as organic, fair-trade and health food products to mainstream, high profile brands.

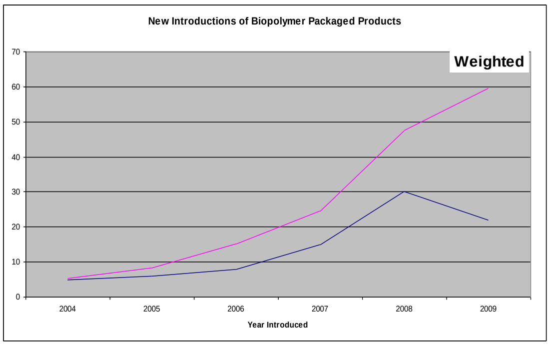

Figure 2.– Growth in BDP Applications (weighted and un-weighted) 2009 based on six months recorded data, doubled for full year

Drivers and Barriers (Limiters)

There are a number of factors which to a greater or lesser degree have had or will continue to have an influence on the development, uptake and growth of bio-derived polymers within the packaging sector. A logical division would be to separate those exerting a positive influence from those exerting a negative one, however it is possible for one factor, such as bio-fuel development, to have the potential to do both, in that it competes for natural resources but also provides a larger, more stable market allowing longer term investment and development to improve efficiencies and reduce costs. As can be seen from Fig. 3, there are numerous influences at play with direct and indirect influences and interrelations. The most important of these are listed in Table 3.

In the initial stages of bio-polymer development, market drivers such as consumer demand, oil prices and long term security of supply appeared to be the most influential. More recently policy and government initiatives including legislation such as the EU packaging waste directive EU 94/62/EC, and initiatives such as the EU's Lead Market Initiative (LMI) "Accelerating the development of the Market for Bio-based Products in Europe", the ADEME's "Bio-products Guidbook for Greener Procurements" and the USA's "Federal Bio-based Products Preferred Procurement Program" have the power to become the major influencers in BDP growth and uptake.

	Primary	Secondary
+ Positive	**The limited availability and increasing cost of fossil resources (oil and gas) and the need to secure National energy supplies.** **Policy and legislation, particularly within the area of man made climate change, sustainability and economics.** **Consumer demand driven by the growing awareness of the need for sustainable management of earths resources.**	**Organic & 'green' brands** looking for packaging that supports their corporate and brand values. **Retailer pressure** and initiatives such as the Wall-mart scorecard system and single use carrier bag reduction initiatives **Pollution** from plastic litter that does not breakdown in the environment and leads to the suffering and death of both land and marine life. **Increasing environmental damage** caused by the extraction of oil from harder to reach and more environmentally sensitive reserves such as deep sea, oil sands, polar regions etc.
- Negative	**Higher costs and more complex supply chains including capacity limitations and restricted supplier base.** **Technical performance limitations compared to fossil derived polymers in manufacturing, application and use** **Lack of clarity and quality of data regarding their overall environmental benefits. Requires detailed and independent LCA of whole process including a wider range of impacts.**	**Recycling** and the contamination of existing plastic waste streams. Not an issue with 3rd generation class b polymers produced from bio-ethylene etc. **Land availability** and competing demands of food production, energy production and preservation of natural habitats. Land is also a finite resource.
Both -+	**Bio-Fuel Development –** Competes for resources but also provides volume, secure market, and commercial scale. **Pressure Groups –** Opinion polarised between opposing fractions – Environmentalists v Business as Usual (BAU)	**New technologies** such as GM Foods (Genetic Modification) and Nano-composites. Obvious benefits in terms of performance and production efficiency improvements but concerns about their safety could lead to consumers rejection, particularly by the early adopters of these environmental products.

Table 3 Key factors influencing growth of BDP packaging

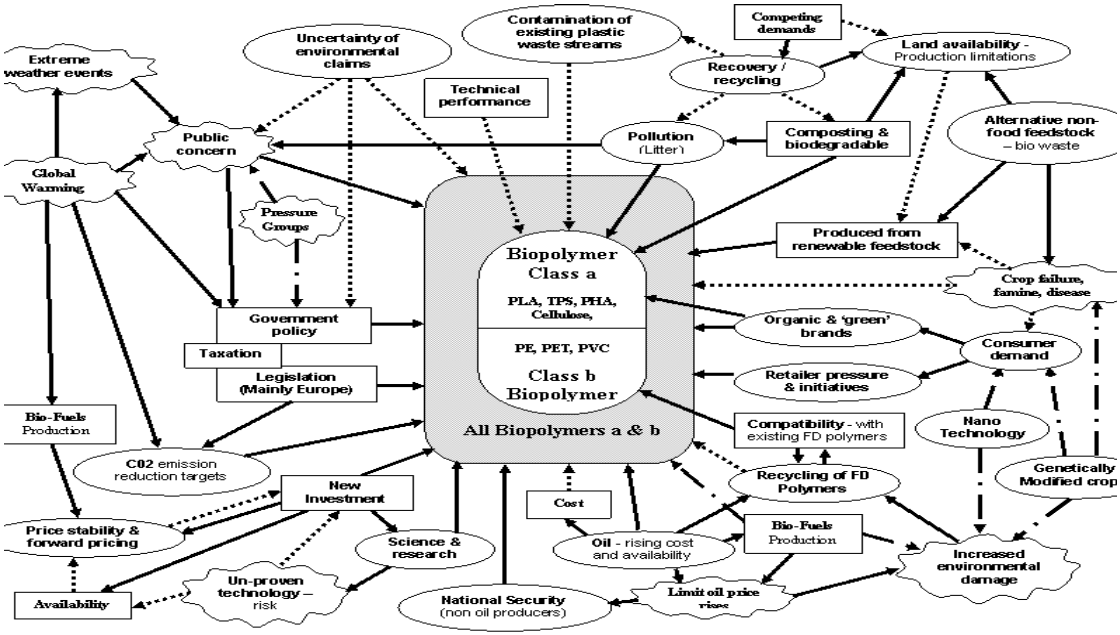

Figure 3 – Map of social, environmental, economic and political influences on Bio-derived polymer packaging

Knowledge Gaps and LCA review

Life cycle assessment (LCA) is a well-established methodology commonly used to quantitatively evaluate the environmental impacts of products and processes (ISO 2007). The method has been applied to the evaluation of BDPs for the purpose of producing environmental product declarations for commercial use, and in academic studies. Despite the development of a standard methodology for applying the LCA method, a large degree of subjectivity remains, with results often highly dependent on the definition of the system scope and boundaries.

In order to develop an understanding of the reasons for these contradictions, a systematic review of publicly available LCA reports from the academic and commercial literature was conducted, spanning a time period between 1997 and 2009. Twenty-five studies were identified and were reviewed in terms of various criteria, including the following:

- Scope of the study (life cycle stages) – which life cycle stages were included?
- Scope of the study (data quality) – how reliable was the data used?
- Scope of the study (environmental impact categories) – which environmental impact categories were evaluated?
- Independence of the study – was the study conducted or sponsored by a BDP producer?

The results from this review are summarised in Figure 5.

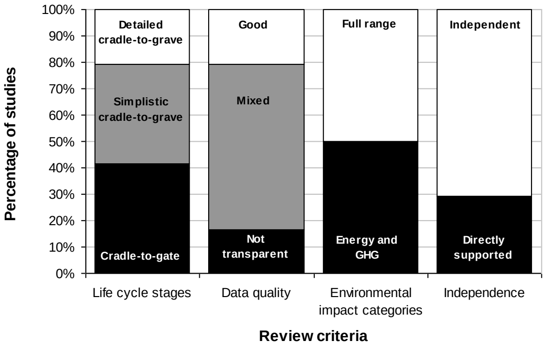

Figure 4 Review of LCA studies against review criteria 2009

production of BDPs. These cradle-to-gate studies were in general performed by BDP producers (e.g. Kurdikar *et al* 2001; Vink *et al* 2003; Vink *et al* 2007; Novamont 2009) and based on data from industrial processes. The publication of cradle-to-grave studies in which all life cycle stages were considered in any detail was scarce.

More often, cradle-to-grave studies built upon existing cradle-to-gate studies by making simplistic assumptions regarding the application and end-of-life management of BDPs and BDP products (e.g. Johansson 2005; Harding *et al* 2007; Madival *et al* 2009). The use of simple assumptions in generating scenarios for cradle-to-grave analysis is valuable in providing an indication of environmental life cycle impacts in the absence of real data. However, results from such studies must be treated with caution, and may be readily misconstrued by a non-expert reader.

The quality of data was identified as being good in situations where primary data sources, such as BDP producers, had been used. While a small number of studies were not transparent in their data sources, the majority relied on a mixture of primary and secondary data. The application of allocation rules, especially with regard to greenhouse gas and energy accounting, was identified as a cause for concern. In particular, the incorporation of Renewable Energy Credits (Vink *et al* 2007), and discounting for the use of biomass power generation systems in production facilities could bias results. Despite a high degree of transparency in the use of such allocation methods, again the concern is that a non-expert reader could misunderstand the implications of such technical aspects of LCA methodology.

It was interesting to note that around half of the studies identified focussed only on the quantification of environmental impacts associated with energy consumption and greenhouse gas production. While this reflects the current political agenda, more comprehensive studies showed that other impact categories, such as eutrophication potential, are also important in the production of BDPs (Harding *et al* 2007) and should not be ignored.

Finally, it was interesting to note that although around one third of the studies identified could be directly linked to parties with commercial interests in the promotion of BDPs, the majority of LCA studies in the published literature appeared to be conducted by independent parties. This is reassuring, since it demonstrates an appropriate level of scrutiny is being applied to the evaluation of these new materials, especially important where a methodology with tendencies to subjectivity, such as LCA, is concerned.

Concluding Discussions

Bio-derived polymers have developed and grown dramatically in the past six years, both technically and commercially, however much of the scientific knowledge underpinning this growth is fragmented and somewhat controversial. From our study we believe that BDP use is about to enter a new phase of rapid growth. The rationale for this is based firstly on the increasing influence of the three key drivers to BDP growth identified in this report (Table 3) and other published works, such as the recent Pro-Bip report (Shen et al, 2009) and the lead market task force report on bio based products in Europe (COM(2007) 860 final). Secondly, with particularly relevance to 'Class B' BDPs, from the reduction / removal of two of the key barriers to growth. The third barrier being the need for clarity through LCA etc on the exact environmental benefits of BDPs.

In terms of the three key drivers: firstly, the number and influence of ‘artificial’ drivers, such as government policy, legislation and environmental taxes and levies has been increasing rapidly. Secondly ‘natural drivers’ such as consumer demand are likely to grow driven by a significant growth in marketing and reporting of environmental issues, in particular global warming and climate change. Thirdly, future increases in oil and gas prices are likely to reach new highs when demand returns to the global markets as economies emerge from recession.

In terms of the three key barriers identified: Technical performance and end of life issues are not relevant to the new and growing Class B BDPs. These bio-ethylene derived polymers such as PE, PET and PVC are identical to their FD counterparts. Secondly, cost and availability, one of the biggest issues for mainstream use, has to a degree been circumvented by these Class B – BDPs as they are able to be mixed with FDPs in any quantity so allowing the impact of cost and supply to be managed (A leading global soft drinks manufacturer is proposing to use up to 30% of BD PET in bottles for some of their products). Cost and supply of these Class B polymers is also being helped by the major increase in bio-fuel development. Significant investment has been made into developing large scale bio-ethylene plants to meet the EU and US targets of 10% bio fuel by 2020. This has provided a large and guaranteed market for the production of ethylene, from which the BDPbs can benefit, using this to provide economy of scale and reliability of supply.

However, all this is taking place without solid and uncontroversial scientific data in place to direct and underpin the decisions and choices that are being made. There is a need for further and urgent LCA studies, particularly in the area of BDP application and ‘end of life’ management to clarify their real environmental benefits and to identify the most suitable immediate applications for their use. In addition, comparisons should be made between materials (Class A and Class B) to determine which provide the greatest benefits longer term and what are the main technical, commercial and social challenges that must be overcome, to create a long term and sustainable packaging market for these materials. It is intended that these findings will then support the future development, selection and implementation of bio-derived polymers in those areas of packaging application which deliver the greatest environmental, sustainable and ecological return.

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Appendix 2

Conference paper – CIRP 2011

Introduction

This paper was presented at the 18th CIRP International Conference on Life Cycle Engineering, Braunschweig, Germany, May 2nd- 4th 2011 and published in the conference proceedings.

Eco-design tool to support the use of renewable polymers within packaging applications.

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Abstract

Bioplastics derived from renewable polymers such as sugars, starches and cellulose, have attracted significant interest from companies looking to reduce their environmental footprint. New production capacity and improved materials have resulted in their increasing adoption for mainstream consumer products packaging. However questions remain regarding their overall environmental benefits and how the maximum environmental gain can be achieved. These uncertainties highlight the need for a decision support tool to aid the packaging design process. This paper examines the issues surrounding bio-derived polymer use and discusses the development of an eco-design tool to assist in their rapid and efficient adoption.

Keywords:

Eco-design, Renewable Materials, Biopolymer Packaging

1 INTRODUCTION

The annual global production capacity of bio-derived polymers (BDPs) has been forecast to grow annually by 37 percent, reaching 2.33 Million tonnes by 2013 [1]. This rapid growth has been sustained as BDP packaging markets expand from the early adopters producing niche and synergetic items such as organic drinks and whole foods, to global mainstream products and brands such as cola, crisps and chocolate [2]. A key driver of this success has been the desire for environmentally friendly, sustainable packaging and the belief that BDPs meet this requirement. To a large degree this view has been fostered both from the claims made by manufacturers, and the obvious emotional attraction towards a material with a natural, renewable pedigree. More recently this market demand has been further encouraged by various government initiatives which promote and support the procurement of 'bio-based' and 'sustainable' products [3].

Unfortunately, the current level of scientific understanding of the environmental benefits achievable from these materials, particularly post gate (use and end of life stages), is inadequate or simply nonexistent [4]. This is supported by the findings of a review of 25 published LCA reports from the academic and commercial literature, spanning the period between 1997 and 2009, Figure1 [2].

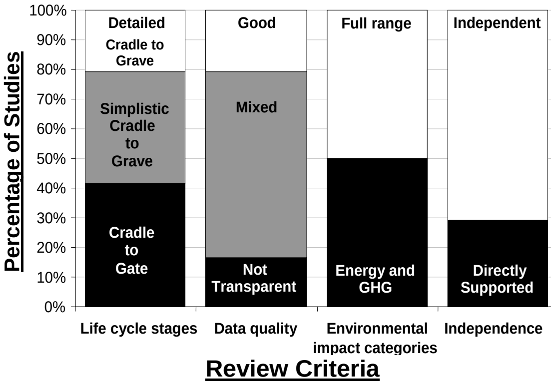


Figure 1: Findings of LCA study against review criteria (2009) [2]

Specific questions, regarding the impact on food production, genetic modification, consistency of supply, technical performance, contamination of conventional polymer waste streams and biodegradability, remain unanswered. Whilst government support for renewable materials is desirable if not essential, caution should be taken to avoid the premature or inappropriate adoption of a particular BDP or technology, which in turn could hinder future development, particularly if the environmental claims are later proven to be false or vacuous.

This paper begins with an overview of the main BDPs used as packaging, their key applications and potential market growth. It then considers the various issues that surround the use of BDPs and identifies the key barriers and drivers to wider and greater adoption. In light of the growing need for sustainable manufacturing, we then consider the range of eco design and decision support tools that are available to industry to assist in the identification, selection, application and assessment of BDP packaging. This study, through an assessment of the key strengths and weaknesses of each tool, aims to identify the key unfulfilled needs in this area and thus establish both the need and the framework for the new eco-design tool. The paper concludes with an overview of this new tool, its proposed structure, and how this will meet the unfulfilled needs of industry.

2 BIO DERIVED POLYMERS IN PACKAGING

2.1 Key BDPs: Their Origins and Evolution

Whilst a small number of BDPs, such as cellulose film, have maintained a commercial presence in the packaging market, the resurgence in interest of BDPs as a viable alternative to conventional polymers began during the 1990's in response to increasing pressure from both consumers and government to reduce the environmental impact of packaging culminating in the EU directive 94/62/EC on Packaging and Packaging Waste [5]. Whilst the directive and subsequent legislation does not promote the use of bio derived materials over conventional ones, it obligates companies to formally consider the environmental aspects of their packaging designs in addition to the commercial and technical ones.

The first generation of BDPs were limited to low technical performance applications, in the past decade a new generation of materials have been developed, capable of being used for processed, long shelf life products such as crisps, cereals, chocolate and beverages. Figure 2 identifies the key BDPs used in packaging and the main source/route to production [5]. As their availability and costs have improved, so their uptake has increased. The most commercially successful of these to date are PolyLactic Acid (PLA) and Bio-ethylene based PE and PET. Both these materials have been used in full or in part across a wide range of pack formats and processes such as; stretch blow molded bottles, injection molded components, thermoformed trays and flexible films (including high barrier laminated films for coffee and crisps).

1.1 Packaging Applications Study

To understand how the application of BDPs for packaging has evolved, an online review of published announcements for new product launches in BDP packaging was undertaken. This included searching the websites and press archives of all the main BDP manufacturers, associated trade press and the key industry bodies, associations and institutes for; the environment, packaging and plastics industries, dating back to 2004.

It is an expected and an accepted limitation of this review that as a material becomes established, i.e. first generation bio-polymers such as cellulose film and foamed starch chips, it will probably become less noteworthy of comment and so its frequency will decline even if use actually increases. Also, the results recorded launch activity, not ongoing use, and so should not be viewed accumulatively.

When these new introductions are plotted against their launch dates, a picture emerges of a gradual annual growth in use, see Figure 3 lower line. However, this only shows the frequency of product launches and does not consider the individual significance of each new introduction in terms of the BDP used. As it is not possible from these announcements alone to ascertain accurate data with regard to the volume of sales, material use, specific barrier properties, transmission rates etc, a simple weighting factor was applied instead

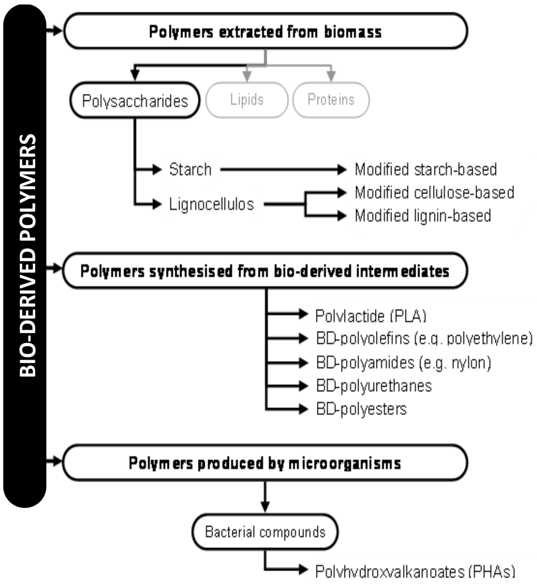


Figure 2: Overview of principal bio-derived polymers (adapted from [6]). *Flows in bold indicate routes to the principal BDPs.*

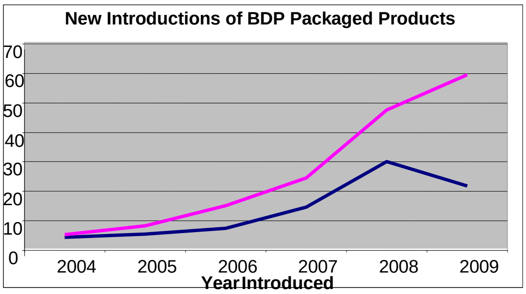


Figure 3: New Introductions of BDPs based on company announcements from Jan 04 to May 09 - Colwill et al[1]

The factor used was allocated based on five easily assessable key criteria: Brand awareness, Company size, Launch market size, Potential market size and Application complexity. A weighting factor was applied for the first four criteria of 1x for local, 3x for national or 5x for global. For the fifth criteria, application complexity, a weighting of 1x for low complexity, 3x for medium (thermoformed/laminated), 5x for high complexity (injection molded, blown, high barrier). Once applied the sum total was divided by five to a final value of between 1 and 5 for each application.

When this data is re-plotted with the weighting factor it shows a much sharper growth curve (figure 3, upper line) particularly during the last two years, which might indicate that BDPs are entering a new accelerated growth phase. This would lead to higher growth than other data has previously suggested, such as BDP production capacity investments [1], which forecast growth by 2020 to reach 3.5 Mt capacity and earlier projections which forecast volumes of between 2.5Mt and 4.17Mt by 2020 [6]. In addition, when the two graphs are compared it suggests that in addition to a general increase in use, these new BDPs are gaining wider market acceptance, moving from niche, synergetic applications such as organic, fair-trade and health food products to mainstream, high profile brands.

1.1 Capacity and New Investments

In anticipation of the future demand, a number of companies have invested in plant for the production of BDP's The annual global production capacity of BDPs, based on company announcements, is now forecast to grow from 0.36 Mt (million metric tonnes) in 2007 to 2.33 Mt in 2013, an annual increase of 37 percent [1]. Figure 4 shows the projected growth in the production capacity of Class A and Class B BDPs. Class A BDPs include PLA, PHA. TPS and cellulose, whilst class B BDP's are those which are identical to conventional polymers apart from the original monomer source, such as PE and PET derived from bio-ethylene.

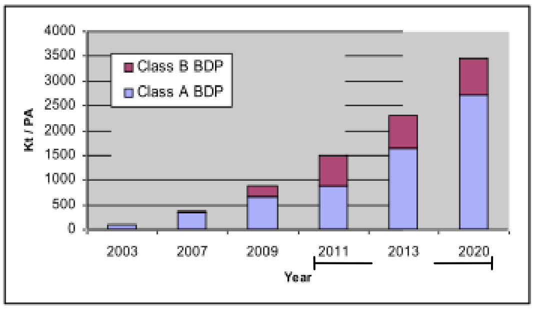


Figure 4: Global production capacity of bio-derived polymers based on company announcements up to May 2009 [2].

1 THE KEY ISSUES TO USING BDPS IN PACKAGING

1.1 Drivers and Barriers

There are a number of factors which to a greater or lesser degree have had or will continue to have an influence on the development, uptake and growth of bio-derived polymers within the packaging sector. The most significant of these are listed in Table 1, however whilst many of these have a foreseeable resolution as technology or commercial advances are made, there are two key issues that in our view will require a much more substantial and collaborative effort to resolve, these are:

- Development of alternative feedstocks to avoid direct competition with food production (materials and land use) in order to provide a sustainable and scalable polymer source.
- Development of new technologies and infrastructure to enable the conservation of this resource and to avoid contamination and disruption of existing conventional polymer recycling.

In terms of positive influences, policy and government initiatives such as the EU's "Lead Market Initiative", the ADEME's "Bio-products Guidebook for Greener Procurements" and the USA's "Federal Bio-based Products Preferred Procurement Program" have the potential to be a major influence on BDP growth and uptake. The other major driver will be cost and performance parity as the gap between BDPs and conventional plastics narrows.

1.2 Packaging Design and Development

The varied and cross departmental responsibilities for packaging functions within a business add yet further complexity to the packaging development process, (Figure 5). Whilst the majority of functions are clearly aligned to a particular hierarchical structure, e.g. Finance and Accounting, Sales and Marketing, Engineering and Production, packaging impacts on almost all aspects of the business and often the control hierarchy will change on a regular basis as a means to adjusting an imbalance caused by that particular departmental bias, (finance, marketing, operations etc). This has often resulted in the packaging function 'ownership' being rotated through different business functions on an almost cyclical basis, Manufacturing, Marketing, Finance/Purchasing etc. One approach some companies have taken is to break the packaging functions into three separate groups as shown in Figure 5.

	Factors influencing BDP adoption
Positive	The limited availability and increasing cost of fossil resources (oil and gas) and the need to secure National energy supplies. Policy and legislation, particularly within the area of climate change, sustainability and economics. Consumer demand driven by the growing awareness of the need for sustainable management of natural resources. Other factors include: Organic and green brands, Retailer pressure, anti litter action and increasing environmental problems and severe climate changes.
Negative	Higher costs and more complex supply chains, including capacity limitations and a restricted supplier base. Technical performance limitations compared to conventional polymers. Lack of clarity and quality of data on the overall environmental impacts. Other factors include: Greater recycling of conventional polymers and problems of waste stream contamination by BDPs, Land availability and food production.
Both	Bio-Fuel developments compete for limited feedstock resources but also provide volume, a secure market, and commercial scale. Pressure groups can influence public opinion and government policy. However, views are polarised for and against at present. New technologies such as genetic modification and nano engineering bring huge potential benefits but also huge potential risks. Tend to polarise opinion particularly within an already sensitized and sceptical public.

Table 1: Barriers and Drivers to increased BDP adoption.

This allows each function to be more closely aligned with the most appropriate business functions. However this then creates the problem of ensuring that communication and cooperation between the groups maintains the skills and potential of the whole, particularly important in the development of new packaging.

It is clear that the decision to adopt BDPs for packaging within an organization will not be restricted to any one group, function or skill set. For the tool to be fully inclusive it needs to engage actors at all levels and stages depending on their abilities and needs. This is true not just within the company but also throughout the wider supply chain and where possible engaging the consumer.

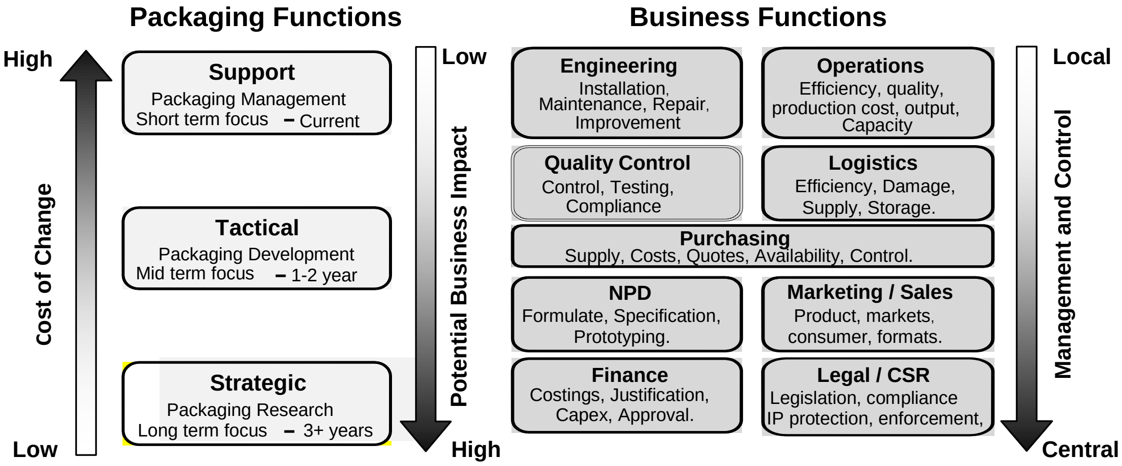


Figure 5: Key functions of a packaging dept and their relation to other key business areas.

1 AN OVERVIEW OF CURRENT ECO DESIGN TOOLS

A study of academic papers and industrial reports was carried out across a range of eco-design tools. This included individual [7, 8] as well as multiple [9,10] tool reviews. The main focus was on packaging but general eco-design tools that could be used for packaging design were also considered. The review focused on a number of criteria, four of which have been selected for comparison in Table 2 and Figure 6. These are: Sustainability Considerations (Which of the three key pillars of Sustainability, Environmental, Economic and Social, were considered by the tool), Life Cycle Approach (What life cycle stages were considered), User Guidance (Which of the 5 guidance criteria listed were output to the user) and User Inclusiveness (of the user groups listed, how many would the tool be useful and accessible to).

In all, 40 tools were assessed using a combination of previous design tool studies and individual tool reviews. The main criteria and sub divisions are listed below in Table 2. It is clear that significant interest exists, within a range of industries operating at various stages along the supply chain, in the development of tools for the purpose of improving the environmental design of packaging as well as using renewable materials.

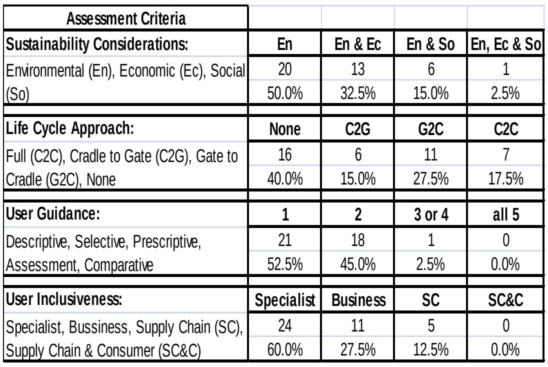
2 FRAMEWORK FOR THE TOOL

2.1 Introduction to the tool

The development of the proposed tool arose from the recognition of the necessity to ensure that the limited capacity of bio-polymers needs to be directed towards applications where the greatest overall environmental benefit can be achieved. It was envisaged that a tool which could help achieve this through the appropriate selection and application of materials within the pack design and development process, would be widely welcomed by industry. [11]. It is also clear that a direct comparison of BDPs with their conventional counterparts would be misleading as to the future potential that could be achieved once the BDP industry and markets mature. The ability of the tool to evaluate the pack based on future potential, as well as current performance, is essential if it is to play a strategic role [12].

2.2 Key requirements of the tool

The requirements for the eco-design tool were identified from both a literature review and through industry consultation. Six key requirements are listed in Table 3. The features highlighted in bold are those which are considered to be absent or inadequately provided for in existing tools. These are supported by similar findings in a recent Canadian Government report [10].



Assessment Criteria				
Sustainability Considerations:	**En**	**En & Ec**	**En & So**	**En, Ec & So**
Environmental (En), Economic (Ec), Social (So)	20	13	6	1
	50.0%	32.5%	15.0%	2.5%
Life Cycle Approach:	**None**	**C2G**	**G2C**	**C2C**
Full (C2C), Cradle to Gate (C2G), Gate to Cradle (G2C), None	16	6	11	7
	40.0%	15.0%	27.5%	17.5%
User Guidance:	**1**	**2**	**3 or 4**	**all 5**
Descriptive, Selective, Prescriptive, Assessment, Comparative	21	18	1	0
	52.5%	45.0%	2.5%	0.0%
User Inclusiveness:	**Specialist**	**Business**	**SC**	**SC&C**
Specialist, Bussiness, Supply Chain (SC), Supply Chain & Consumer (SC&C)	24	11	5	0
	60.0%	27.5%	12.5%	0.0%

Table 2: Results of Ecodesign Tool Study against review criteria.

Feature	Requirements
Full Life Cycle Perspective	Should consider performance across the whole life cycle, cradle to cradle.
Sustainable Focus	The tool should consider all three pillars of sustainability: **Social** as well as Environmental and Economic.
Strategic and Tactical	The tool should support strategic decision making looking at future performance as well as current properties and performance.
Holistic and Inclusive	Should be usable and provide guidance across the whole supply chain, including consumers.
Total Stage Support	Should provide support at each stage of the design / development process through a series of individually targeted but connected tools.
Feedback	Tool should provide feedback which allows progress to be measured and improved.

Table 3 Key features, requirements and intended users of the tool.

2.3 Proposed Structure for the Packaging Eco-Design Tool

The tool aims to support the decision process at three different levels depending on the expertise of the user, availability of input data and required detail of output data as shown in Figure 6.

This will include; type of application or product to be packaged, selection and use of the BDP material, pack construction, manufacturing process, distribution and retail methods, consumer use and 'end of life' management.

The three separate but interlinked tools, which can be used independently or in combination, are as follows:

EcoD2 Part 1 - Justification Level

Assesses the potential for including BDP packaging as part of the company's overall packaging / corporate sustainability strategy:

Method: A series of questions, in the form of a decision tree, are asked which highlight the key threats and opportunities, strengths and weakness for the adoption of BDPs by the company, both short and long term.

Result: The results from the questions will give a top level guidance on how the company should proceed. This might include statements such as:

- BDPs are not compatible with your current business practice and strategy.
- BDPs will provide significant benefits but not within current cost limits.
- BDPs are a viable option for your company, proceed to next level.

EcoD2 Part 2 - Specification Level

Identify specifically which BDPs will meet the essential and desirable requirements of the specific application regarding technical, commercial and operational feasibility:

Method: A technical relational database of all BDPs commercially available will allow specific requirements to be searched and the suitable polymers to be identified. Each of the key known factors can be entered via a series of blank forms or lists, e.g. Barrier, Strength, Elasticity, Compression, Melt temperature, Process etc.

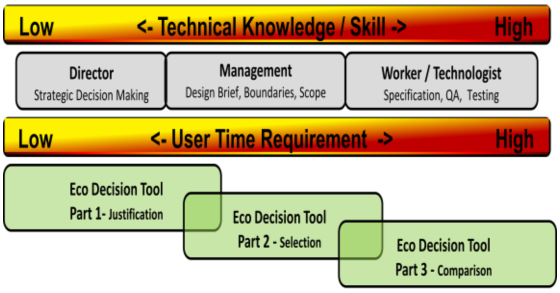


Figure 6: The relationship between User time and skill levels with the three separate Tools parts 1 - 3.

Result: The results from this stage will be in the form of single datasheets and comparative performance graphs to include:

- Data sheet for each BDP that meets or exceeds entered criteria.
- Multiple BDPs can be plotted against single or multiple criteria.
- Potential future scenarios can be used to give a predicted performance potential.

EcoD2 Part 3 – Comparison Level

Compares different pack concepts across a range of criteria and supports the final selection process as part of existing new pack development procedures.

Method: Each concept is measured in terms of its material content, material type, performance, size, dimensions, weight and key features. These are input into a program via a menu system which performs the necessary calculations.

Result: The final concepts will be measured in terms of their individual material components, total pack performance, construction costs, cube, environmental footprint etc. The results from this stage will be in the form of single page report that summarises the key benefits, costs and performance of each concept.

1 CASE STUDY – A BAG FOR ORGANIC SALAD

The following example illustrates how this proposed eco-design tool might have been used during the decision, design and development process for a possible packaging development project. We created the following scenario as the basis for the case study: A company (UKCM) supplies a leading UK supermarket with pre-washed mixed organic salad. Both the manufacturer and retailer had been meticulous in ensuring that the product meets the highest standards of purity, quality and environmental performance. It was desirable and logical therefore that the packaging should reflect those product values. The category manager of the retailer and the marketing director of the manufacturer/supplier arranged a working meeting to discuss and agree a way forward to achieving this goal. During the meeting the Eco-design Tool (EcoD2) Part 1 was used to investigate whether BDPs might provide a viable packaging solution.

EcoD2 Part 1 - Justification for Using BDP Packaging.

With only a limited time available a quick answer was required to be derived from information that was readily available to the two 'high level' experienced but not technical business people.

Method: The company's Marketing director accessed the tool online to assess the suitability of BDPs as a means to package their product in a 'carbon neutral' way. Following a decision tree based question and answer process, he input top line information about the company, its product and overall aims and objectives, a process that took approximately 10-15 minutes.

Result: The tool provided guidance as to the suitability of BDPs, the main implications of its use and recommended next steps on how the company should proceed:

- Based on the product's brand values, market positioning, premium price, technical/performance requirements and potential end of life disposal options, there is a strong possibility that BDPs could provide a suitable packaging medium for this product
- The BDPs which meet the product requirements and are within a viable geographic range would be Starch, Cellulose or PLA based. Option buttons would be provided which would allow the company to produce a chart comparing specific properties of these 'base' materials on factors such as cost, bio-degradability and technical properties. A list of suppliers could also be generated within a given geographic range.
- The suggested next steps, assuming that the commercial and technical requirements fell within the given range, would be to select and contact the suppliers of these materials initially with a specification / brief to be prepared from the information added to the system so far and to be further populated by the technical and operational staff within the two organizations.
- The specification is sent to the supplier and linked to the tool. The supplier's response is entered into the tool online. This allows comparisons between the different supplier/material options to be compared.

EcoD2 Part 2 - Specification Level

In order to complete the specification, the technical/packaging manager/technologist identifies specifically which commercially available grades of BDPs from which suppliers meet the technical and performance product requirements. The materials that fulfill these needs are added to the specification.

Method: A technical relational database of all BDPs commercially available allows for specific requirements to be searched and the suitable polymers to be identified. Each of the key known factors can be entered via a series of blank forms or lists. e.g. Barrier, Strength, Elasticity, Compression, Melt temperature, Process etc.

Result: The results from this stage will be in the form of datasheets and comparative performance graphs. In addition the qualifying materials and supplier information can be transferred from the database to the specification sheet for transmission to the supplier. This can also be used to automatically request quotes, technical data and trial sample materials.

EcoD2 Part 3 – Comparison Level

Following initial trials of the different materials, the comparison tool is used by the designer to compare the different pack concepts across a range of criteria and to use this data to support the final selection process as part of in-house new pack development procedures. The outputs of this information can be stored and made available to consumers via the tool or other medium such as the retailer's website.

Method: Each concept is measured in terms of its material content, material type, performance, size, dimensions, weight and key features. These are input into a program via a menu system which performs the necessary calculations.

Result: The final concepts will be measured in terms of their individual material components, total pack performance, construction costs, cube, environmental footprint etc. The results from this stage will be in the form of single page report that summarises the key benefits: environmental, commercial, social and physical performance for each concept. In addition, comparative charts and graphs can be produced for each of these key criteria.

1 SUMMARY AND CONCLUDING DISCUSSIONS

Whilst the growth and development of bio-derived polymers has continued to gain momentum over the past few years, there is a clear danger that this could stall if confusion regarding their overall environmental impact is not removed. A number of methods for categorizing BDPs have been suggested, such as by feedstock type or production method, however in terms of application and end of life management there are two main divisions: Class A, unconventional polymers extracted or synthesized from renewable feedstock but not compatible with conventional plastics and Class B, conventional polymers synthesized from bio-ethylene e.g. polyethylene and PET. It is these former class A bio-polymers, such as PLA, Cellulose, PHA and TPS, that require further investigation in this area in order for them to achieve their environmental potential.

In parallel with the growth of BDPs, there has been the pressure on companies to reduce their manufacturing environmental footprint particularly that associated with their packaging. To-date this has focused primarily on waste reduction and recycling and in some instances materials substitution, such as replacement of PVC with PET. As a result, a number of guides and tools have been developed to assist companies in achieving these goals; including Life Cycle Assessment, Retailer Scorecards and Green Design Guides. However these guides tend to be limited in the guidance that they give, strategic and early design stage use, the range of impacts measured, the cost and complexity of use and/or the over simplification of the results. In particular for BDPs, it is important to consider the likely future impacts as technologies, costs and methods advance.

As packaging is a multi disciplinary function that extends across the majority of traditional business departmental boundaries, it is essential that this tool provides a mechanism for a wide range of users with different skills and requirements to input into and benefit from its use. Furthermore, the use of the tool should extend beyond the traditional business operations and be available to the whole supply chain. In particular the information should be available to the consumer to enable them to make informed choices about the products they buy which in turn will drive further environmental investment and development by industry.

It is clear therefore that a holistic approach is needed to eco packaging design if the future challenges of sustainability are to be achieved. It is also clear that better guidance at both the strategic and tactical level on the selection and use of bio-derived polymers in packaging applications is required by industry to avoid 'green wash' and ensure the greatest environmental, sustainable and ecological return is achieved from this renewable but ultimately finite resource. The eco-design decision tool which we are developing for packaging will be a significant step towards achieving these goals.

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Appendix 3

Conference & Journal Paper – BEPS 2011 / JOOE 2012

Introduction

This paper was presented at the Bio-Environmental Polymer Society Conference (BEPS) in 2011 and published in the Journal of Polymers and the Environment (JOOE), in 2012. For copyright reasons, the version provided in this thesis is incomplete and not the final published version.

A HOLISTIC APPROACH TO DESIGN SUPPORT FOR BIOPOLYMER PACKAGING

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The growing interest in biopolymers as a packaging material, particularly from companies looking to reduce their environmental footprint, has resulted in these renewable materials becoming more widely accepted and used in the packaging of high volume, mainstream products such as corn snacks and beverages. Whilst traditionally the selection and specification of materials during the pack design process was largely based on factors which could be expressed and compared economically, with biopolymers, particularly where the primary rationale for their use is an environmental or sustainability based one, the factors on which decisions are based are not directly comparable or expressible in a single standard unit. Furthermore, these factors have a significant strategic element that requires a broader range of horizontal and vertical input, both within the business and the wider supply chain. It is therefore essential that a holistic approach is taken during the packaging design process, when considering the use of biopolymers, to ensure that the final packaging meets the original intent and overall requirements of the business. A tool designed to support this holistic approach will therefore need to include inputs from a diverse range of stakeholders both within the manufacturing organization and externally, from across the supply chain. Current eco-packaging design decision support tools are generally restricted to specialist users within the pack design process, such as designers or packaging engineers, and provide largely tactical rather than strategic support and guidance. This disconnect, between the inclusivity of stakeholders and strategic support required for a holistic design approach, and the exclusivity and largely tactical support given by current eco-design decision support tools, indicates a clear need for a new decision support tool for sustainable pack design using biopolymers. This paper examines the need for a holistic approach and strategic support in this context and outlines the framework for a new eco-design decision support tool for biopolymer based packaging developed to address current shortcomings.

1. INTRODUCTION

The development of biopolymers has been driven largely in response to the growing concerns regarding the sustainability of conventional polymers and the environmental pollution caused by plastic packaging waste (Lim *et al*. 2008; Shafiee and Topal 2009). The majority of plastics in use today are manufactured from fossil fuels such as crude oil, natural gas and coal (American Chemistry Council 2010). These non-renewable resources are being rapidly depleted by a range of human demands of which fuel for energy production, heating and transport is the largest user: fossil fuels currently provide approximately 80% of the world's primary energy needs (Goldemberg 2006). Plastics production meanwhile accounts for around 4-5% of global crude oil consumption compared to the 87% that is incinerated (Queiroz and Collares-Queiroz 2009; Plastics Europe 2009). Resource depletion is only part of the problem; carbon dioxide produced when these fossil fuels are burnt is believed to be a major contributor to global warming, which could have potentially devastating social, economic and environmental consequences in the future if not addressed. As demand for fossil fuels continues to increase, so the pressure to find new reserves pushes exploration into increasingly challenging and environmentally sensitive locations multiplying the environmental impact of extraction and use (Bergerson and Keith 2006; Howarth *et al.* 2011).

Biopolymers offer a potential solution to both of these dilemmas. Firstly, in terms of production feedstock, synthetic polymers derived from fossil fuels such as crude oil, are replaced by polymers derived from renewable resources (e.g. trees, corn, sugar cane and algae). Secondly, many of the bio-derived polymers retain the biodegradable properties of the original feedstock enabling them to be composted and to breakdown completely in the environment, so reducing the problem of litter contamination. Thus as the technical performance and affordability of these materials has improved, so the adoption of biopolymers has grown from niche synergetic applications to mainstream, high volume global brands, particularly as leading companies look to capitalize on their consumers' / customers' demands for more eco-friendly products. This observed trend is likely to continue as the pressure on companies to reduce their carbon emissions increases.

Whilst the manufacture of biopolymers from renewable feedstocks is a strong indicator as to their sustainability, fossil fuels are still expended at various stages during their life cycle. When other factors such as water and land use are considered the sustainability benefits of these materials becomes less obvious. This observation is supported by the fact that despite numerous life cycle assessments and other environmental impact studies in this area, the overall environmental benefits of these materials in packaging applications remains contentious and contradictory. (Colwill *et al*. 2009). This is particularly significant since in contrast to conventional polymers, the rationale to adopt biopolymers in packaging is justified primarily on a perceived environmental benefit, often at a premium cost.

2. PACK DESIGN PROCESSES

The processes discussed in this paper are based on the design of primary packaging for consumer and retail markets. Primary packaging is usually in direct contact with the product and forms the primary sales unit as retailed to the consumer. In addition to the creation of a new pack from first principles, the re-design and re-engineering of packaging is particularly applicable to biopolymers, as material substitution may be effected without any visible change to the pack structure or appearance.

2.1 The traditional ‘conventional polymer’ packaging design process

To support an understanding of the packaging design process, the tasks involved in the conventional packaging design process were grouped into five main stages; Preparation, Feasibility, Design, Development and Implementation (Figure 1(a)). The preparation stage is a data gathering, sorting and communication exercise. The two key milestones in this stage are the initial preparation of a design brief and the subsequent development of a design specification. Next is the feasibility stage which involves the identification of suitable materials, formats, and processes that meet the technical and commercial essential requirements for the design. If no material can be identified then either the design specification or brief needs to be modified, or in exceptional circumstances the company may develop a new material usually in partnership with third parties. This material development is shown in Figure 1 (a) as an alternative process stage parallel to the feasibility stage indicating that wider material searches would continue.

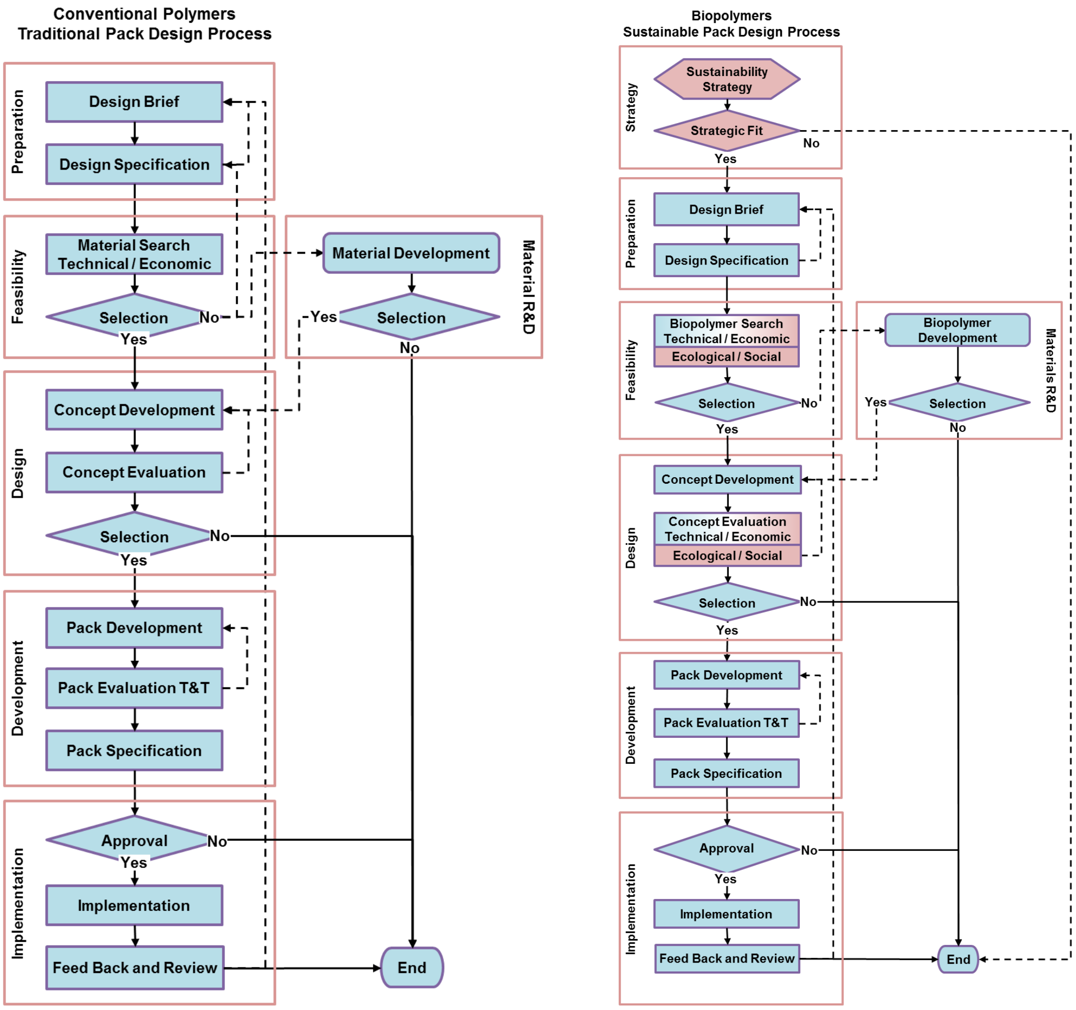
During the design stage, the pack concepts are conceived, created, evaluated and selected. This may involve a number of iterations from initial brainstorming of ideas, to visuals and finally three dimensional models or working prototypes. Usually one concept is selected for the development phase which will involve testing and trials. At the end of development the final specification for the pack will be produced, which contains all the information required for its manufacture. The final stage is implementation, which begins with approval of the pack across the business and continues through its introduction with monitoring and feedback of its performance.

2.2 The Alternative Sustainable ‘Biopolymer’ Packaging Design Process

The alternative sustainable design process for biopolymer packaging, as depicted in Figure 1 (b), has six key process stages; Strategy, Preparation, Feasibility, Design, Development and Implementation, as well as an alternative Material Research and Development stage that runs in parallel with the Feasibility stage. The key differences in this process, when compared to the conventional polymer packaging design process, are the addition of the Initial Strategy stage and modifications to the Feasibility and Design stages. The other stages in this process are consistent with the traditional pack design process.

The addition of the Strategy stage is required to ensure that the potential benefits achievable through the adoption of biopolymers are in line with the company’s strategic goals and expectations. With a traditional pack design activity, the strategic goals are well understood by the business and may include, cost reduction, increased margins/sales and profit improvement. With the sustainable design process, the strategy driving the interest in biopolymers is more complex involving social and environmental factors. It is essential that before embarking on an expensive packaging development exercise and product launch, realistic expectations are established based on the strategic goals which can be easily communicated and translated into design actions which in turn can be included in the design Brief and Design Specification produced during the Preparation stage.

The Feasibility and Design stages have been modified from the traditional design process through the inclusion of sustainability considerations, metrics and assessment criteria in the material database fields and in the concept assessment/selection criteria. It should also be noted that due to the immaturity of biopolymer discovery, it is much more likely that companies will have to take an active role in biopolymer Research and Development (R&D) than with conventional materials.



b) **b)**

Figure 1: a) Key Stages in a Traditional Packaging Design Process using Conventional Polymers, b) Key Stages in a Sustainable Packaging Design Process using Biopolymers

2.3 Comparison between the two processes

By comparing the two processes illustrated in Figure 1, clear differences can be seen between the two approaches. These differences are summarised in Table 1. Firstly the question of, whether biopolymers can form part of a company's packaging strategy and contribute towards their overall business sustainability goals, needs to be addressed. This is a high level decision, most likely taken at board level or by senior management, and would primarily be concerned with the broad commercial, financial, environmental, social and technical implications of using biopolymer packaging

Process Stage	Sustainable Design for Biopolymers Packaging	Traditional Design for Conventional Polymer Packaging
Strategic	The decision to use biopolymer packaging is primarily a strategic one and so should be relevant and contribute to these corporate sustainability objectives.	Not Required Strategic goals already communicated and understood within the business.
Preparation	Essential and desirable design requirements identified and then specified.	Essential and desirable design requirements identified and then specified.
Feasibility	Identifies technical and commercial feasibility of design objectives, as well as sustainability goals	Identifies technical and commercial feasibility of design objectives.
Development (Alternative Process)	More likely	Less likely
Design	Uses sustainability criteria to direct design in addition to basic commercial and technical criteria.	Design decisions informed by basic commercial and technical criteria.
Development	Standard company testing and trialing procedures followed	Standard company testing and trialing procedures followed
Implementation	Standard company procedures followed	Standard company procedures followed

Table 1: Comparison of Key Process Stages between traditional and Sustainable Packaging Design (highlighted cells indicate a significant change in the process)

These strategic goals for the business, which include sustainability, must be accurately and simply communicated to the packaging design stage. The traditional method of a design brief is used to achieve this but with additional ‘sustainability’ goals included. This design brief is then expanded into a design specification, which includes all the economic, technical, brand, product, manufacturing, logistics and sustainability requirements, prioritized as essential or desirable. This process is achieved through consultation within and across the business areas that are impacted by the proposed changes at every stage of the pack’s lifecycle and would usually be carried out at middle management level within the business. This is an iterative process as, in order to develop a realistically achievable design specification, changes may be required to the original brief.

This design specification would then be used to carry out a material search for commercially available biopolymers that meet the essential and, where possible, desirable requirements of the specification. Once all the potentially suitable materials have been identified, an initial selection process based on the most promising and potentially beneficial biopolymers would be made. If no suitable material can be found, then material research and development can be explored. If successful the material(s) would then be selected for use in the concept development.

The development of packaging concepts is largely the same for both processes, although support may be required by the designer on the biopolymer material properties. However the assessment of concepts will require, in addition to traditional criteria of economic, technical, aesthetics etc., social and environmental impacts to be addressed. These along with the economic impacts are assessed throughout the whole pack life cycle for each pack concept. These are then compared against each other and conventional polymer counterparts. The concept evaluation can be an iterative process, informing the design process, as well as being used for final selection.

The remaining steps of both processes involving the development, testing, trialing and implementation of the final pack design are largely the same, with the exception of the biopolymer packaging evaluation and approval activities requiring the inclusion of additional sustainability data. Before outlining the framework for a holistic and integrated approach to the sustainable design of biopolymer packaging, based on the key differences identified and discussed in this section, it is worth considering other approaches that have been used to address the issues of incorporating sustainability issues into the strategic decision making and design process.

3. Approaches to Sustainable Strategy and Design

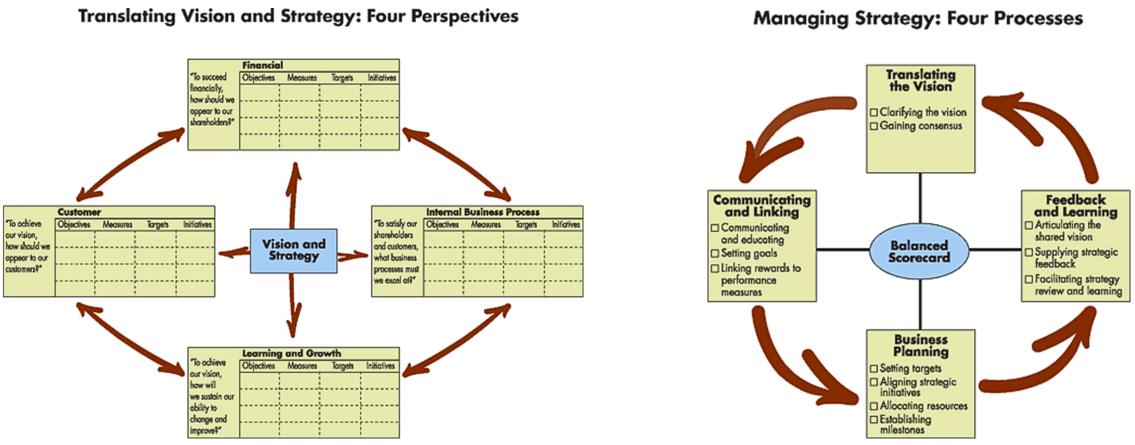
A financially based strategy, such as described for conventional polymers, is simple to communicate and can be easily translated into direct operational activities. Likewise the results of these activities can then be measured and reported back within the existing financial and auditing structures, so enabling the effectiveness of the strategy to be determined. However, with biopolymers, many of the drivers for change are not easily translatable into economic measures. This issue is not just limited to biopolymers: studies carried out by Kaplan and Norton (1996) concluded that increasingly, long term strategic objectives were becoming more difficult to translate into simple financial measures and targets. These findings led them to develop the balanced scorecard (BSC) which later evolved to incorporate sustainability issues.

3.1 The Balanced score card and sustainability

The Balanced Scorecard (BSC) was initially developed as a mechanism for assessing a company's performance beyond its traditional financial measures. Kaplan and Norton's initial assertion was that the long term success of a company was no longer limited to financial capital, but that soft factors, such as customer focus, knowledge base and intellectual property, were also important. These key factors were captured in the BSC as four perspectives; financial, customer, learning and growth, and internal business process (Figure 2a). From this diagram it can be seen that these four perspectives are all inter-connected, forming an integrated set of objectives and measures. This is achieved by defining goals, supported by appropriate long-term strategic objectives (lagging indicators) and identifying the specific competitive advantages of the business that can be used to achieve these objectives (leading indicators).

Thus for each specific strategy, key performance drivers will be identified for each of the four perspectives. However, since a loose set of indicators and measures would be ambiguous and ineffective, these must be prioritized in terms of their strategic relevance. By creating a hierarchical cause and effect network, through causal linking of the leading and lagging indicators towards the long term financial goals, the resources of the business can be prioritized to those activities that will best promote the conversion and communication of the strategy.

This original concept of the BSC quickly evolved during its use in industry into a much broader strategic management system, linking long term strategy with short term operational actions. Whilst the initial concept of the BSC applied a primarily top down approach, three additional processes were added that linked these long term objectives with the short term actions. These four key processes, as shown in Figure 2b are: Translation of the strategic vision; its communication and linking to performance measures; business planning; and feedback and learning. The diagram highlights the cyclic relationship of these processes, showing how the feedback and learning phase has the potential to influence and inform the strategy providing a continuous mechanism for improvement, refinement and re-evaluation of strategic goals.



(b) (b)

Figure 2: The Four Perspectives and Four Processes of the Balanced Scorecard

Source: Robert S. Kaplan and David P. Norton, "Using the Balanced Scorecard as a Strategic Management System," Harvard Business Review (January-February 1996): 76 and 77.

This functionality of the balanced scorecard, to allow non-financial success factors to be considered and incorporated within the business strategy, made it an obvious starting point for bringing corporate social responsibility (CSR) and sustainability management into the heart of business; through the inclusion of social and environmental factors into the core 'economic' management system. The need to reconcile these three factors or 'pillars' of sustainability (Social, Economic and Environmental) was noted at the 2005 World Summit (United Nations General Assembly 2005). These terminologies evolved to reflect a more corporate perspective becoming known as the 3 Ps: People, Profit and Planet, also referred to as the triple bottom line (Elkington 1994).

A number of approaches have been proposed on how a 'sustainability balanced scorecard' (SBSC) could be achieved (Johnson, 1998; Bieker, 2003; Figge et al. 2001, 2002; Epstein and Wisner, 2001; Schaltegger and Dyllick, 2002; SIGMA 2002; Gminder and Bieker, 2002). Figge *et al.* suggest two alternative approaches to achieving this, either by integrating the environmental and social sustainability factors into the existing four perspectives of the BSC, or introducing a fifth 'non-market' perspective. Furthermore, both of these two approaches can be extended with an additional second step incorporating the results from the higher level BSC of the strategic business unit into a 'derived social and environmental scorecard' (Figge *et al.* 2002).

3.2 Applying the SBSC to the Biopolymer Eco-design tool

The BSC is a tool to implement strategies, translating vision into action; it does not create the strategy. Likewise the Sustainability BSC (SBSC) provides a mechanism and method for incorporating and communicating sustainability within the core business strategy and, whilst it does not itself create the strategy, its use "may help to detect important strategic environmental and/or social objectives of the company" (Bieker 2003). However, the time and effort involved in developing an SBSC is considerable and usually involves significant learning, due to an initial lack of knowledge of business leaders on the sustainability issues and strategies.

Bieker (2003) identifies a number of difficulties with implementing SBSC in practice: Firstly the enormous amount of patience, power and persistence required over long periods of time by top 'powerful' management; secondly the lack of will of the incumbent 'sustainability' managers to relinquish their sphere of influence by integrating sustainability into traditional management structures; and thirdly a lack of sustainability policy and/or strategies within the business at the start of the process.

The rationale for having an SBSC and the difficulties encountered by Bieker when implementing it are indicative of the problems faced by an organization when considering the use of biopolymer packaging. Firstly, the motivation for this change would almost certainly be based on environmental or sustainability improvement and so would lie outside the traditional financial decision making. Secondly, whilst the feasibility of using biopolymer packaging is largely an operational decision, the motivation to do so is predominantly a strategic and tactical one. Ensuring that the original motivation (strategy) for using biopolymer packaging is not lost during the realization and feasibility process (action), requires that the strategy can be clearly communicated based on a realistic expectation of what biopolymer packaging can achieve and also requires a degree of knowledge and understanding by senior management on the issues surrounding packaging, sustainably and biopolymers.

The first requirement of a biopolymer eco-design tool should be to overcome these difficulties identified by Bieker (2003), by providing guidance through a supported step by step process that helps the management establish the role that biopolymers could play in achieving the company's strategic sustainability goals. The results of this process would then communicated down through the business in a similar way to that achieved by the SBSC. In our research, by focusing the scope of the tool solely on biopolymers and their comparison with their conventional polymer counterparts the complexity of tasks are managed at each stage thus keeping the time and effort required to a minimum, regardless of the level of knowledge of biopolymers or existing sustainability strategy.

4. A Holistic Approach

The Design Council (2011) lists the roles of packaging as threefold: to sell the product; to protect the product; and to facilitate the use of the product. In order to be able to fulfill these roles the packaging must meet many varied and sometimes conflicting demands and requirements. These include legislative, financial, manufacturing, technical, logistical, marketing, branding, promotional, environmental, and disposal. In fact it is often the case that packaging will have to meet multiple departmental requirements arising from a business and its supply chain, which are in direct conflict with each other, such as pack security versus ease of opening, differentiation versus standardization, and cost versus performance.

4.1 Vertical and Horizontal Integration

It is therefore unsurprising that the packaging design process requires input from key internal departments as well as suppliers and customers within the supply chain. To fully appreciate the complexity of the design process it is helpful to have a basic understanding of how packaging change is managed within the typical consumer goods manufacturer. How companies incorporate the various packaging functions, such as packaging design, within the corporate structure will vary according to its size, sector and culture. An illustration of a common corporate structure is given in Figure 3, based on the authors' experience. This divides packaging into three key functions: Operational Support (Short Term View), Design and Development (Medium Term View) and Research and Development (Long Term View) and shows which departments are most likely to 'host' this particular packaging function in terms of organizational hierarchy: Thus strategic packaging research will most usually report to the director of R&D whilst operational support would report to the Purchasing or Operations director.

Relationships between Packaging and Business Functions + Supply Chain

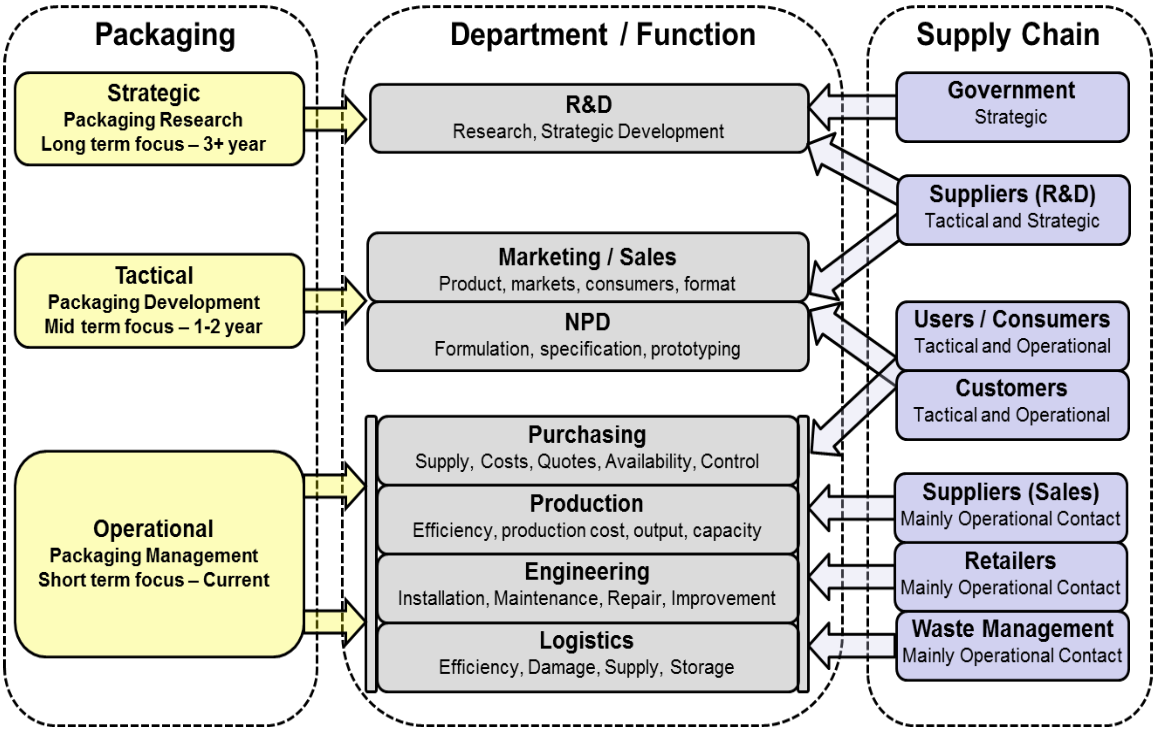


Figure 3: Illustration of a common organizational structure and reporting hierarchy of packaging functions within a typical Brand Owner Manufacturer and its relation to the wider supply-chain.

Finally Figure 3 indicates which key actors in the supply chain are most likely to have interaction with these packaging and departmental functions. Packaging suppliers for example would predominantly be engaging at the operational level but through their R&D and product development may also have tactical and strategic relationships with the company in the development of new packaging or materials. In this arrangement a new packaging material, such as biopolymers, might be identified by the strategic packaging function during its early development phase. The key focus, at this stage, would be to establish the potential commercial advantage delivered by this new material to the business, the associated costs and the probable timescale for change. If a business case can be made then, at the appropriate time, it would be taken forward by the packaging development group. Here the material would be tested and trialed and a full cost benefit analysis undertaken. If approved, this would then be passed to packaging management/operations to implement, involving extensive production and market trials and a rolling implementation across the range of products. During and after implementation, the performance of the pack would be monitored in the marketplace.

It is also worth noting that the cost of changing a pack at the end of the design process is much more costly than at the beginning. As strategy is determined at board or senior management level, whilst tactical and functional decisions are made in the later stages by middle management and skilled employees, any disconnect between these two extremes in the process could have severe consequences on the effectiveness and impact of the design change. Figure 4 illustrates how these key packaging functions relate to the business areas in the context of horizontal and vertical integration. An effective decision support tool must take into account the need for inclusivity both within the business and across the wider supply chain as the decision to adopt biopolymers for packaging within an organization will not be restricted to any one group, function or skill set. For a tool to be fully inclusive it needs to engage actors at all levels and stages by matching their abilities and meeting their needs.

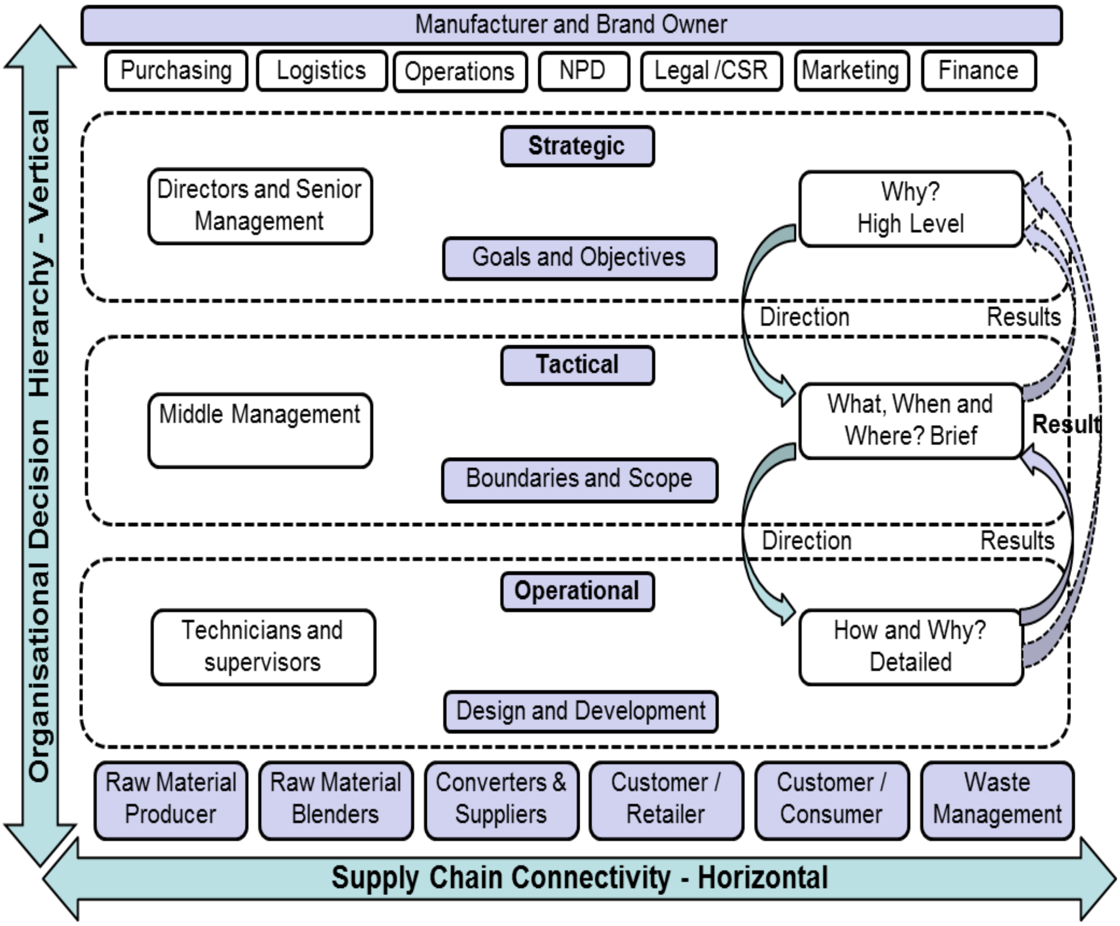


Figure 4: Key functions of a packaging department and their relation to other key business areas

5. THE FRAMEWORK

The Holistic Integrated Sustainable Design (HISD) framework for biopolymer packaging proposed in this research is concerned solely with biopolymers in packaging applications and the conventional polymers being replaced. Whilst there are many factors that might affect the selection of materials and design of a pack, for this framework, only those factors relevant to the comparison of a biopolymer pack with a conventional polymer pack need be considered. The framework is not intended as an alternative to the existing pack design process or for the wider comparison of different materials or pack formats.

To achieve this goal a systematic approach is proposed to review, select and assess the use of biopolymer packaging in terms of its potential for reducing the environmental, social and economic impacts of conventional polymer packaging. The HISD framework for biopolymer packaging consists of the following three stages and is illustrated in Figure 5.

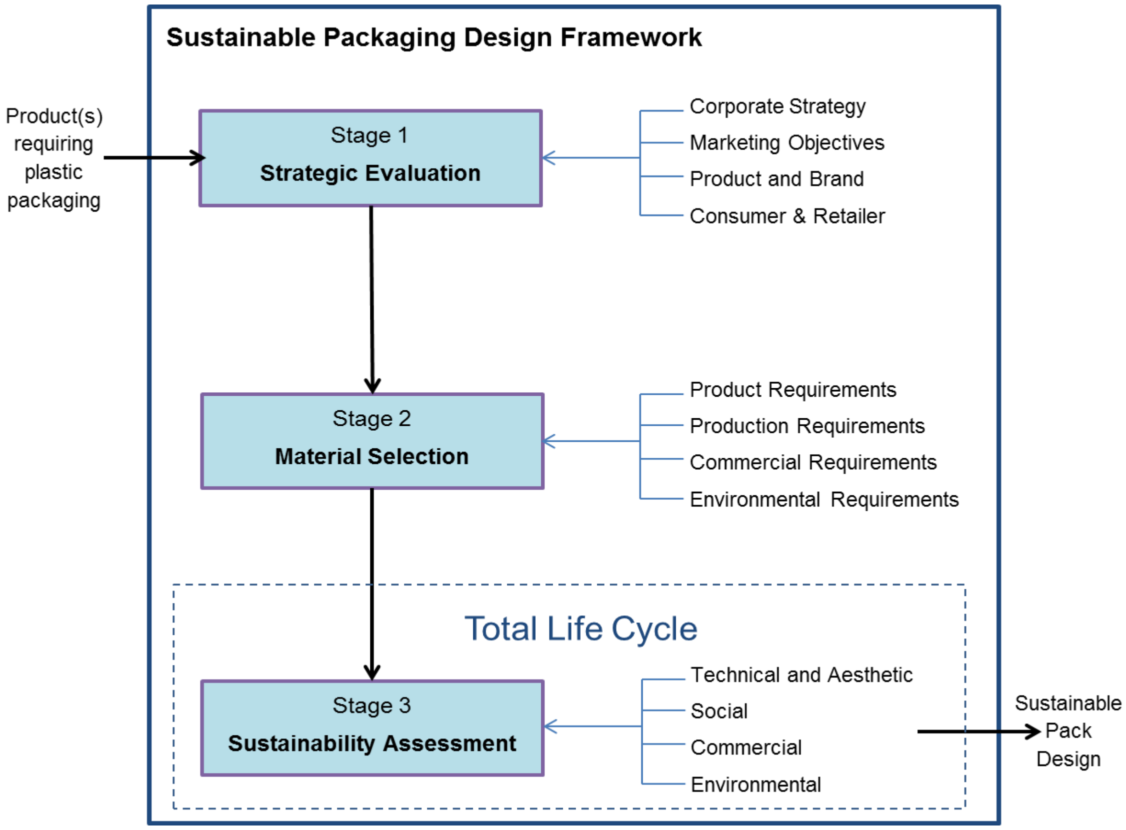


Figure 5: The Holistic Integrated Sustainable Design Framework for Bio-polymer Packaging

The HISD framework firstly establishes the potential of biopolymers to contribute to the company’s Business, CSR and/or Packaging strategies, and then translates these into communicable business actions. These actions then inform the development of a technical, commercial, social and environmental requirements specification, which will be used to evaluate and select the most appropriate biopolymer(s). Finally, a robust life cycle assessment of the selected biopolymer(s) and the incumbent conventional polymer alternative(s) must be undertaken for each proposed pack concept.

This evaluation stage should assess the environmental, social and economic impacts across the whole life cycle and provide a mechanism by which the results for alternative pack options can be compared against each other, and against the original specification and strategic objectives. The complexities involved in integrating this sustainable thinking into the current pack design process are two-fold. Firstly there is the unresolved problem of integrating the three pillars of sustainability into a single assessment process, and secondly there is the difficulty of integrating these additional design considerations and activities into the existing pack design processes and requirements. The tasks involved in each stage of the framework are described in more detail in the following sections.

5.1 Framework for Biopolymer Packaging Functional Stages

The three stages of the proposed HISD framework, as shown in Figure 5, are listed below.

1. Strategic Evaluation
2. Material Specification
3. Sustainability Assessment.

This framework forms the basis for a computer aided Eco-Packaging Design Support tool as illustrated in figure 6.

5.1.1 Strategic Evaluation

The aim of the strategic evaluation is to establish the potential for biopolymer packaging to contribute to the relevant strategic goals of the business and if appropriate, support the translation and communication of these strategic goals into business actions.

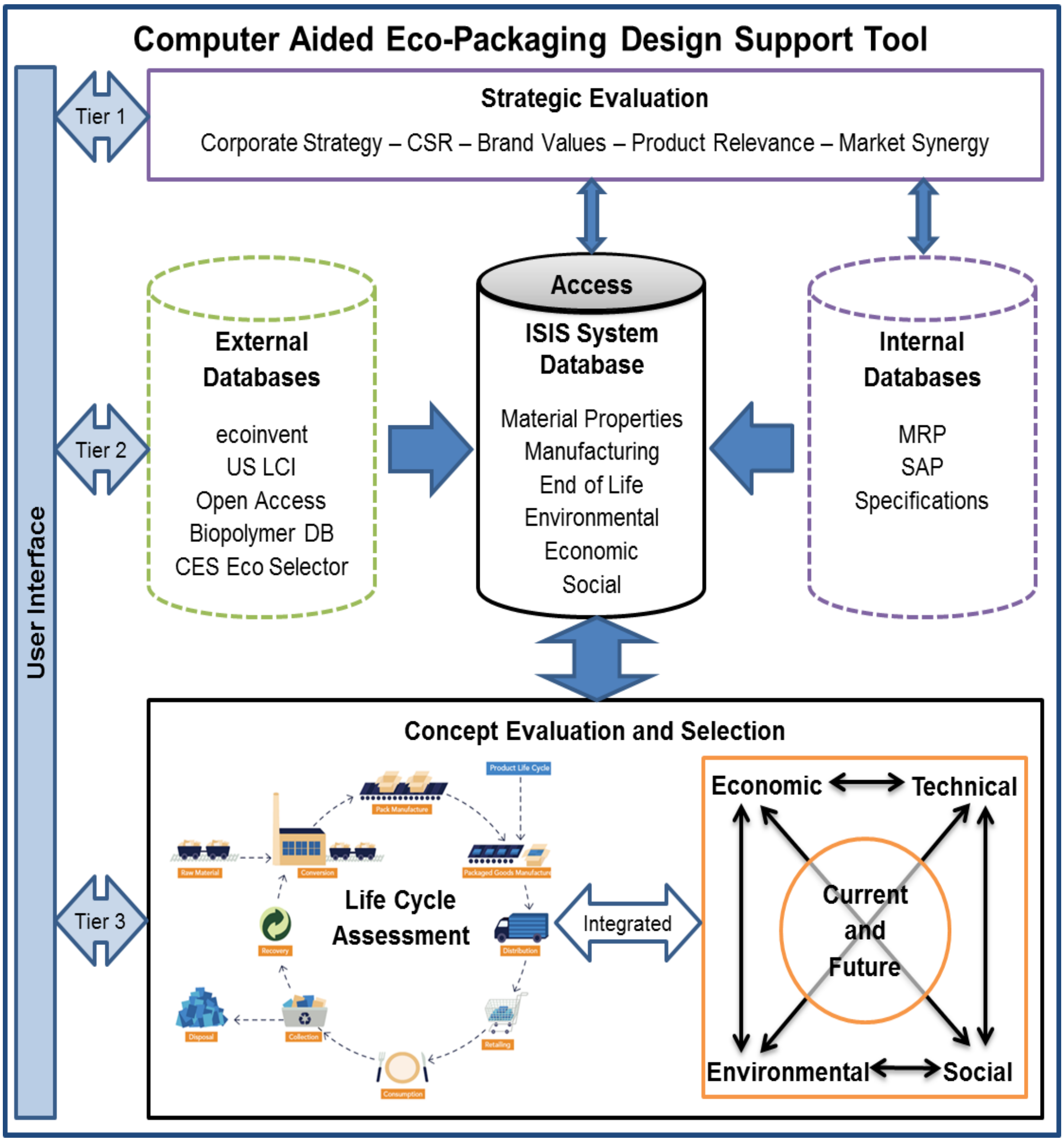


Figure 6: An overview of the EPD Framework implementation through the ISIS (EPD) Tool

Traditionally strategic goals have been relatively easy to communicate in financial terms to the rest of the business. However, when trying to communicate less traditional strategic objectives such as sustainability, responsibility, and knowledge etc., as would be the case with biopolymers, the traditional financial model proves inadequate.

Studies carried out by Kaplan and Norton (1996) concluded that increasingly, long term strategic objectives were becoming more difficult to translate into simple financial measures and targets. As discussed in section 3.1, these findings led to the development of the balanced scorecard (BSC), which was further adapted to include sustainability measures, becoming the sustainability balanced scorecard (SBSC).

As highlighted in section 3.2, there are problems associated with implementing an SBSC which, in the case of biopolymers, would primarily be insufficient existing knowledge and lack of senior management time. Therefore, in the framework presented within the current research, the strategic review stage aims to address these issues by eliminating the need for specialist knowledge and to minimize the senior management time required to get to an actionable result. This is achieved through the following four tasks

d) Definition of current business sustainability strategy
e) Categorization of business
f) Identification of the strategic goals relevant to biopolymer packaging
g) Prioritization and communication of strategic goals

Definition of current business strategy: The strategic review begins with the definition of the existing business sustainability strategy according to the three ‘pillars’ of sustainability – Economic, Environmental and Social. The information entered at this stage provides a reference point for subsequent developments. This task comprises of both free text as well as multiple choice inputs which are used in the subsequent tasks of this stage.

Categorization of business: The second task is to identify and allocate a category to the business. This will be used to inform the identification of strategic goals by allowing the questions to be tailored to the business, thus reducing the time and complexity. Again a multiple choice question format is used, with questions regarding the company size, sector, scope and spend. These are combined with the initial ’strategy’ inputs and analyzed. The results are then used to allocate a particular category to the company, The objective of this being to reduce the senior management time required by creating a more tailored and streamlined process in the final two tasks of this stage.

Identification of the strategic goals relevant to biopolymer packaging: This is the central task of this stage and involves mapping the key strategic sustainability and business objectives against the key properties and impacts associated with biopolymers and biopolymer packaging. These are grouped to include economic, environmental and social factors, as well as technical and commercial requirements.

The outcomes from this stage are threefold: firstly to answer the general question as to whether or not biopolymers can contribute towards the company's strategic goals on sustainability is provided; secondly, the compatibility, relevance and benefits of biopolymers with respect to the product and brand is determined; thirdly, a list of the key strategic objectives that are intended to be met in full or part by the adoption of biopolymer packaging is produced.

Prioritization and communication of strategic goals: Having identified the key strategic goals, the next step is to prioritize them, based on the level of importance to the business. This prioritized list then provides the input for the development of a top level 'design brief'. The design brief outlines the key objectives and strategic goals of the business that are expected to be met in full or part through biopolymer adoption as well as the technical and commercial targets that must be met by the pack design.

5.1.2 Specification and Material Selection

The aim of the specification and material selection is to assist in the identification of potentially suitable materials for the purpose as defined in design brief. However the design brief is a high level document, produced by senior/middle management, which describes the key objectives and strategic goals of the design, but has little detailed guidance on the technical and commercial requirements. In order for the appropriate materials to be selected the detailed pack/material performance requirements must be specified more precisely. Once complete this can be used to identify and select the appropriate biopolymer materials for concept development. As shown in figure 4, it is anticipated that this is likely to be undertaken by lower/middle management with some degree of technical knowledge. The following three tasks must be completed during this stage:

a) Development of a detailed Design/Material Specification from the Brief.
b) Prioritisation and Approval of specification requirements.
c) Identification of suitable biopolymer materials.

Development of a detailed Design (Material) Specification from the Brief: This document, developed initially from the design brief, considers the requirements of the pack (material), in a more detailed, structured and systematic approach. The first step is to ensure that every relevant part of the business and supply chain is represented. Then through a combination of previous experience and consultation, an inventory for the specification can be developed. A template providing the most common requirements could be provided as a starting point for this process, providing both a document structure and tick list of likely considerations.

Prioritisation and Approval of Specification Requirements:

Once the full list of requirements has been produced, these should be prioritized. This could involve the separation into either essential and desirable requirements, or a more detailed division including degrees of desirability. Once complete, this specification document should be approved by the business and can be used later in the business to assess the designs and inform concept/pack selection. However, prior to this the first application would be to identify suitable materials, with the appropriate properties, to meet the specification requirements.

Identification of Suitable Biopolymer Materials:

This would be achieved most efficiently if the attributes of the materials, listed in a database, were directly comparable / searchable with the requirements in the specification. Whilst it is not expected that the database would be able to hold every detail of a material, covering all possible aspects of its performance, it should contain sufficient detail of the most essential attributes. These should be in each of the main performance areas, such as economic, technical, performance, aesthetic, environmental and social impacts to allow material selection to be made at least to the point of short listing. The database would also include contact data for the suppliers of these materials.

5.1.3 Evaluation and Selection

The purpose of the evaluation and selection is to support the designer during the pack development process by providing a rapid mechanism for assessing design concepts and informing design changes using sensitivity analysis. These assessments should adopt a life cycle approach integrating economic, environmental, social and technical impacts. Other factors such as manufacturing and consumer appeal can be assessed using existing tools and processes such line trials, pack testing, focus groups and market research. In addition, as the biopolymer industry is in its early stages of development, whilst the impacts from conventional polymers are increasing rapidly as their feedstock reserves are depleted, indication as to the future impacts should be considered as well as current. This is particularly important to industry that requires payback over a number of years on investments.

6. Conclusion and Further Work

The decision to use biopolymers in a company’s products or packaging extends beyond the usual practical, financial and aesthetic considerations. Biopolymer packaging assessment requires complex multi-criteria decision making and trade-offs and is based on future challenges as well as current ones (including issues associated with finite material, food, land and water resources). By adopting a structured and holistic approach from the start, during the strategic evaluation, the original objectives and expectations of the business can be managed as the design process progresses to ensure the final outcome meets the initial intent.

As packaging has a multi-disciplinary function that extends across the majority of traditional business departmental boundaries, it has been identified by the research that it is essential that any decision support tool provides a mechanism for a wide range of users with different skills and requirements to input to and benefit from its use. Furthermore, the use of such a tool should extend beyond the traditional business operations and be available to the whole supply chain. In particular the information developed within the tool should be available to the consumer to enable them to make informed choices about the products they buy which in turn will drive further environmental investment and development by industry.

It is clear therefore that a holistic approach is needed to eco packaging design if the future challenges of sustainability are to be achieved. It is also clear that better guidance at both the strategic and tactical level on the selection and use of biopolymers in packaging applications is required by industry to avoid ‘green wash’ and ensure the greatest environmental, sustainable and ecological return is achieved from this renewable but ultimately finite resource. The findings, based on the framework outlined in this paper, provide the basis for an integrated eco-design support tool for biopolymer packaging that would provide a significant step towards improving the sustainability of plastics packaging.

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Appendix 4

Journal Paper – PRC-ME 2012

Introduction

This paper was published in the Journal of Plastics, Rubber and Composites: Macromolecular Engineering in 2012. For copyright reasons, the version provided in this thesis is incomplete and not the final published version.

IMPACT OF THE USE OF RENEWABLE MATERIALS ON THE ECO-EFFICIENCY OF MANUFACTURING PROCESSES

The use of renewable materials has attracted interest from a wide range of manufacturing industries looking to reduce their environmental and carbon footprints. As such, the development and use of bio-polymers has been largely driven by their perceived environmental benefits over conventional polymers. However, often these environmental claims, when challenged, are lacking in substance. One reason for this is the lack of quality data for all lifecycle stages. This applies to the manufacturing stages of packaging, otherwise known as 'packaging conversion', where for certain product/production types, a reduction in energy consumption of 25-30% from lower processing temperatures can be offset by an increase in pressure, cycle times and reject rates. The ambiguity of the overall environmental benefit achieved during this stage of the lifecycle, when this is the main driver for their use, highlights the need for a clearer understanding of impact such materials have on the manufacturing processes.

1 INTRODUCTION

The need for a sustainable supply of materials in manufacturing has never been greater. The relentless rise in global consumption, fuelled increasingly by the newly emerging economies, is putting unbearable pressure on the Earth's limited resources. The World Wide Fund for Nature (WWF), in their Living Planet Report 2010, estimate that by 2030 humanity will need the capacity of two Earths to sustain our current lifestyles [1]. This is particularly apparent in the extraction of non-renewable resources such as fossil fuels, many of which are already nearing a peak in supply, the most prominent example being crude oil [2]. Crude oil has many uses, the largest being liquid fuel in transport, however it is also the most widely used feedstock in polymer production, including those used in packaging applications. Finding alternatives to reduce our dependency on crude oil continues to be of the highest priority.

One means to achieving this has been the replacement of oil-derived materials with renewable bio-derived ones. This approach has been advanced in the plastics packaging sector, with the introduction of bio-polymers; plastics made from naturally occurring polymers (mostly derived from plants) such as sugars, starches and cellulose. Bio-polymer packaging has been used commercially, mainly in niche and low performance applications, since the 1980's.
More recently however, the development of higher performance materials, increased production capacity for bio-plastics (see Figure 1 [3]) and more competitive pricing has seen a significant growth in their adoption by leading brand owner multinationals, such as Coca Cola and Pepsico, in high performance applications [4].

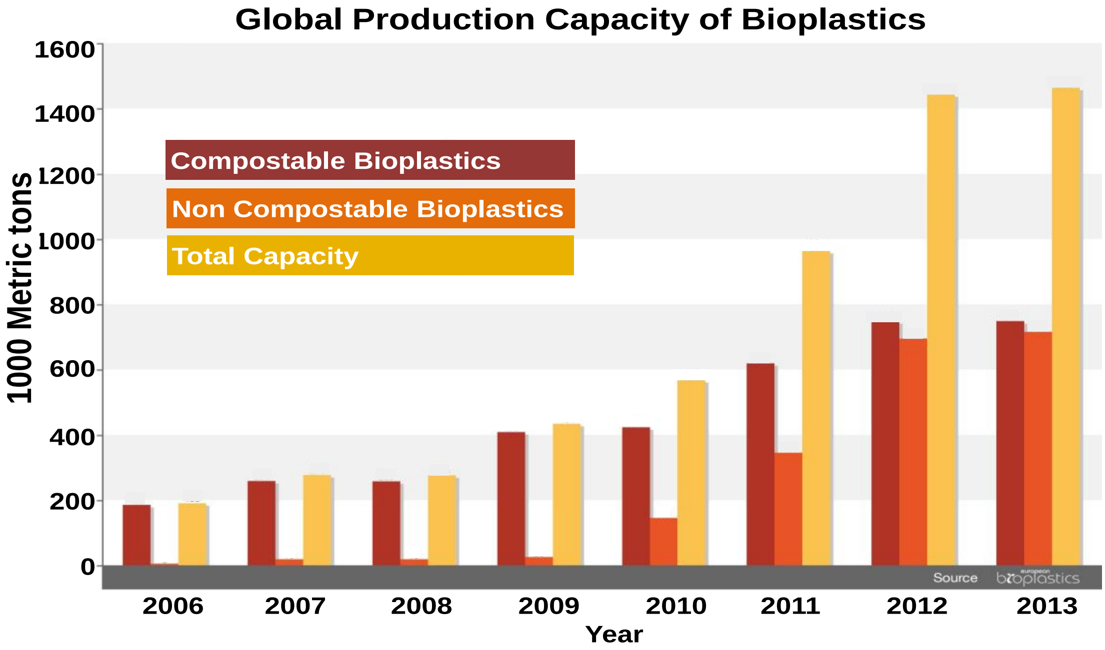

Figure 1: Global Production Capacity of Bioplastics (Sourced from European Bioplastics [3])

One of the main attractions of bio-polymers is their perceived environmental benefits, however despite the environmental claims made by manufacturers, results of independent analysis, over the packs whole life-cycle, are less conclusive. Indeed, various government initiatives have promoted and supported the procurement of 'bio-based' and 'sustainable' products, despite the lack of scientific understanding of the real environmental benefits achievable [5]. A comprehensive review of 25 publicly available life cycle assessment (LCA) reports from the academic and commercial literature, spanning the time period between from 1997 to 2009 confirmed the lack of good quality LCA data for bio-polymer packaging, particularly for the production, use and end of life stages [4].

This paper highlights that, while bio-polymers provide a possible alternatives to conventional thermoplastics for plastics packaging, there are still a number of life cycle issues that need further investigation in particular their environmental impact during the packaging production stage. This paper outlines a method for calculating the 'energy consumption versus waste generated' for three types of packaging conversion processes, based on biopolymers and their main conventional plastic counterparts. These conversion processes represent the three most widely used plastic packaging formats namely; bag, bottles, and trays. A case study based on the production of a 500ml capacity plastic bottle for mineral water has been used to illustrate and assess the key areas of environmental gain and loss.

2 AN OVERVIEW OF BIO-POLYMER TYPES

The number of bio-polymers commercially available for plastics packaging continues to increase, however the first generation of bio-polymers most widely used are: Reconstituted Cellulose (RC), Polylactic Acid (PLA), Thermoplastic Starch (TPS), Polyhydroxylalkanoates (PHA). However, recently the range of conventional polymers produced (in full or in part) from a bio-derived precursor (i.e. bio-ethylene). These include; Polyethylene (PE), Polyethylene Terephthalate (PET) and Polypropylene (PP). This latter group, is often referred to under a number of classifications including: Class B Bio-Derived Polymers, Bio-Conventional Polymers or Non-Degradable Bio-polymers [4, 6]. However, as the processing of these polymers is identical to their oil derived counterparts, this research has focused primarily on the processing of the main first generation bio-polymer, PLA, which has been used commercially for the production of the three aforementioned pack types (i.e. bags, bottles and trays).

3 PACKAGING CONVERSION PROCESES

The final stage during the manufacturing process of most consumer products involves the filling and sealing of the goods into their designated package. In the food and drink sector, this process often involves the inline conversion of an intermediary material such as a reel of film or a pre-form into the individual pack. This conversion process requires key energy inputs, mainly in the form of heat, to shape, mold and/or seal the various packaging types. The three most commonly adopted plastic packaging conversion processes, as depicted in Figure 2, are:

- **Vertical form fill seal** (VFFS) used to manufacture flexible packages for loose products filled by weight, e.g. crisp packets.
- **Stretch blow molding** used to manufacture rigid containers such as bottles for packaging mainly liquid products, e.g. mineral water.
- **Plug assisted thermo/vacuum forming** used to manufacture mainly shallow one or two part semi rigid containers, e.g. trays for chocolates.

From comparison of the physical properties of Bio-polymers and Conventional polymers, it is asserted that thermal stages of these processes are where the most significant difference in theoretical energy consumption exists between the two material groups. However it should also be noted that in practice, other factors such as viscosity, cooling, cycle times and handling will also have an impact on overall energy consumption. The forming, molding and sealing processes are discussed in more details in the following sections.

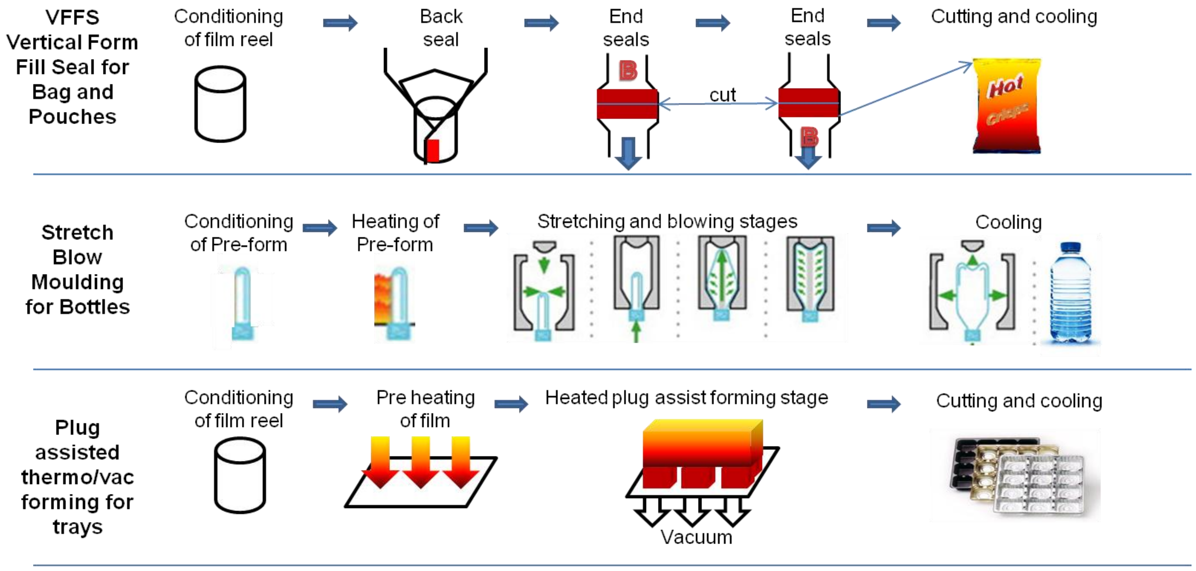

Figure 2: Key stages in three packaging conversion processes

3.1 Vertical Form Fill Seal (VFFS)

The key thermal input in this process, as shown in Figure 2, occur during the sealing of the film firstly down the length of the pack to create a tube, followed by the sealing of the ends to create a sealed bag. In practice these end seals are produced in pairs; the top of the lower bag and bottom of the upper bag are sealed at the same time and then separated by a horizontal cut at the midpoint. To measure the total heat energy used, the sum of the energy used to create all three seals should be calculated. Whilst there are a number of different sealing mechanisms in commercial use each having unique energy values associated with it, by calculating the theoretical energy used to fuse the two layers of film this will allow the comparison of the two material types regardless of the equipment used. Individual machine variations and efficiencies can then be attributed accordingly. The total theoretical heat energy used to seal one bag can be calculated using the equation 1 as derived from the standard equation for heat capacity of a solid with no transition phase:

$$\mathrm{E_{Seal}} = \mathrm{m_{Seal}C(T_{melt} - T_{ambient})} \quad [1]$$

Where:
$\mathrm{E_{Seal}}$ = the thermal energy used to seal a bag.
$\mathrm{m_{Seal}}$ = the mass of material to be fused.
C = the specific heat capacity of the polymer.
$\mathrm{T_{melt}}$ = the seal end temperature in degrees Celsius.
$\mathrm{T_{ambient}}$ = the seal starting temperature in degrees Celsius.

It should be noted that the $\mathrm{m_{Seal}}$ can be calculated from the surface area of the seal multiplied by the film gauge and the material density.

3.2 Stretch Blow Molding (SBM).

As illustrated in figure 2, the key thermal stage in this process occurs during the heating of the pre-form prior to blowing process. Whilst significant energy is used during the other stages of bottle making, this does not vary significantly in terms of the polymer used. The equation 2 can be used to calculate the thermal energy used during this stage of the bottle making process.

$$\mathrm{E_{Mold} = M_{Mold}C(T_{melt} - T_{ambient})}\ \ [2]$$

Where:
$\mathrm{E_{Mold}}$ = the thermal energy used to heat the pre-form.
$\mathrm{M_{Mold}}$ = the mass of material to be heated.
C = the specific heat capacity of the polymer.
$\mathrm{T_{melt}}$ = the end temperature required in degrees Celsius.
$\mathrm{T_{ambient}}$ = the starting temperature in degrees Celsius.

It should be noted that $\mathrm{M_{Mold}}$ can be calculated from multiplying the surface area of the seal, film gauge and the material density.

3.3 Plug-assisted Thermo/vacuum Forming (PaTF)

The key thermal stages in this process occur during the pre-heat and cooling stages, as shown in figure 2. Similarly, the equation 3 can be used to calculate thermal energy used during this process.

$$\mathrm{E_{Form} = M_{Form}C(T_{melt} - T_{ambient})}\ \ [3]$$

Where:
$\mathrm{E_{Form}}$ = the thermal energy used to form the tray.
$\mathrm{M_{Form}}$ = the mass of material to be formed.
C = the specific heat capacity of the polymer.
$\mathrm{T_{melt}}$ = Forming temperature in degrees Celsius.
$\mathrm{T_{ambient}}$ = Starting temperature in degrees Celsius.

It should be noted that $\mathrm{M_{Form}}$ is calculated by multiplying the surface area of the forming, the film gauge and the material density. Furthermore, in the cases where a heated plug assist is used then a smaller additional heat transfer occurs during the forming stage. However this is not included in the calculation in Equation 3.

4 PROCESSING TEMPERATURE VARIATIONS BETWEEN POLYMER TYPES.

The main energy saving in the processing of PLA compared to other conventional thermoplastics occurs during the heating stages. This is primarily due to the lower melting point of PLA, as shown in Figure 3, compared to other widely used packaging polymers. However other factors may also need to be considered in order to evaluate the overall environmental benefits achievable during this processing stage. One of the main considerations in this case is the potentially higher wastage levels associated with PLA as described in Section 5. Whilst the thermal processing calculations of the model are based on actual processing temperatures, wastage levels are theoretical and based on the observed processing limitations of each material.

4.3 Predicting the Impact of Tighter Thermal Processing Windows on Waste Generation.

Whilst PLA has a lower melt point than PET (see Figure 3), it has a much narrower optimal processing window due to its higher temperature sensitivity. The majority of the problems with material distribution and forming will occur at too low temperatures, whilst above the optimal processing temperature, problems with thermal degradation can occur resulting in higher rejection rates [7, 8]. Clearly, The number of rejects will vary case by case, however it is reasonable to assume that on a like for like basis, PLA bottle rejects will be higher than PET due to its greater temperature sensitivity, and this will rise exponentially as temperature fluctuations increase [8,9].

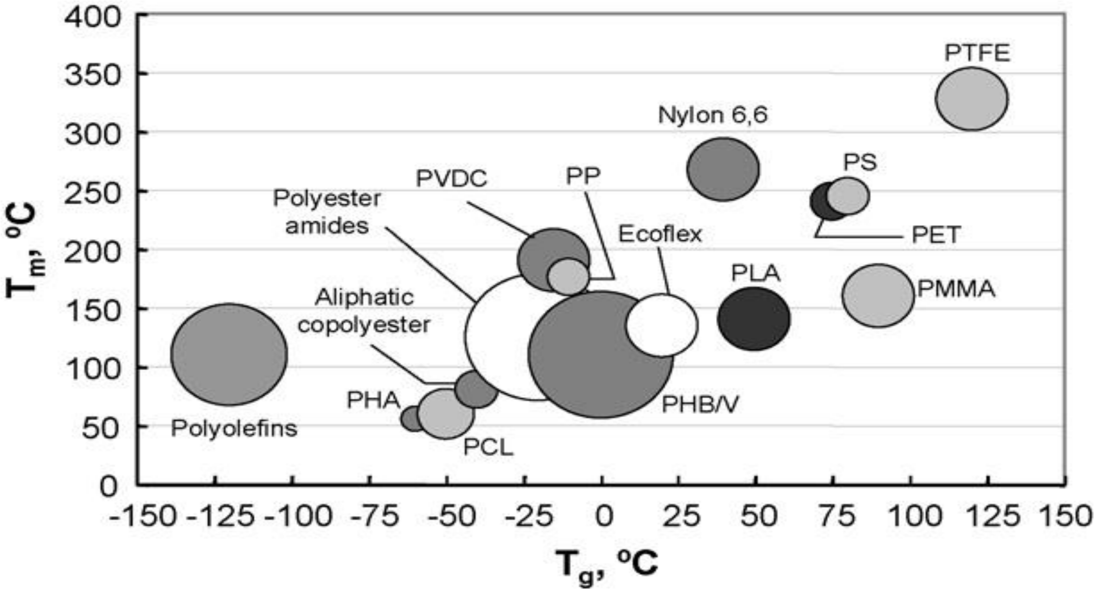

Figure 3: Comparison of glass transition and melting temperatures of PLA with other thermoplastics [7].

Using PLA and PET processing data obtained from both academic and industrial sources (6, 7, 8, 9), the different processing windows of PET and PLA have been estimated. A graph showing the likely increase in rejection rates between PLA and PET, as processing temperature deviates from the optimum, is illustrated in figure 4.

It is proposed that this reject rate will vary, in part, according to how closely the optimum processing temperature can be maintained. Where the control is good, the difference in wastage levels between PLA and PET are unlikely to be significant, however as the level of control drops, the rate of rejects using PLA is likely to increase at a much greater rate compared to PET. The chart assumes a close to 0% reject rate at optimum processing temperature and a 100% rejection rate outside the processing window, as demonstrated in the experiments of Byrne *et al* as highlighted in their study on processing conditions for PLA and PET Polymers (9). An estimation of reject levels between these points was estimated using a standard parabolic distribution curve.

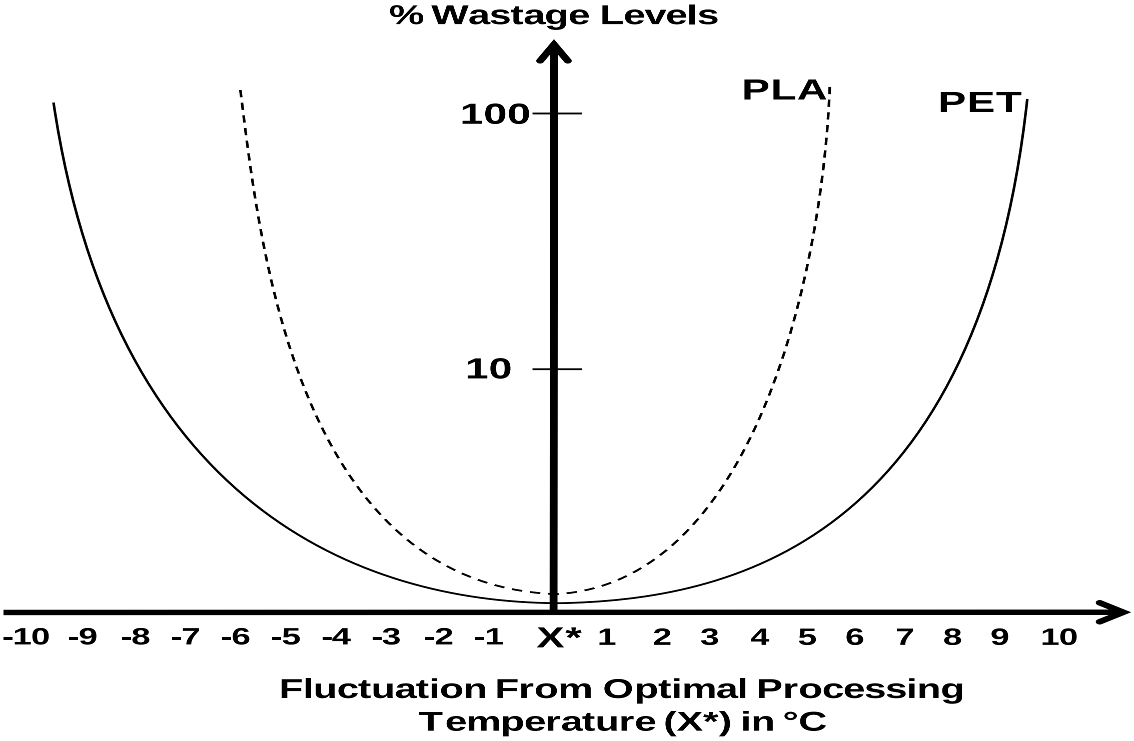

Figure 4: The higher wastage levels of PLA compared to PET due to effect of temperature control fluctuations on processing window size.

5 AN EXAMPLE CASE STUDY

The production of a plastic mineral water bottle is used as a case study to illustrate the issues related to energy used and rejection rates when using two PLA and PET polymers during the thermal processing stages. The data from a typical production system for a 500ml capacity mineral water bottle has been used in this case study, where the neck diameter for the bottle is 28mm and the weight is 24grams. It should be noted that for this case study the same weight was used for both PLA and PET, however opportunities for reducing weight (i.e. a lightweight bottle) using PLA may be possible but outside the scope of this initial study. The various thermal properties for the PLA and PET used are given in Table 1 [10]. It is assumed that one million bottles per year are produced on a twin tool machine operating one 8-hour shift at approx 4 cycles a minute.

The total heat energy used for the stretch blow moulding process has been calculated using the equation 2. All non thermal stages in the process, mechanical, handling and setup etc., were assumed to be equal between the two materials. In terms of calculating wastage, the thermal processing window for PET and PLA was assumed to be +/- 2°C of the optimum processing temperature X*, as per Figure 4. For PET this gives a reject rate of circa 0.5%, whilst for PLA this would give a reject rate of circa 1.5%.

PROPERTY	aPLA	aPET
Thermal Conductivity (cal/cm-sec °C)	3.1 x 10-4	3.6 x 10-4
Specific Heat Capacity (cal/g-°C) above Tg	0.39	0.44
Glass Transition Temp Tg (°C)	55-60	70-79
Crystalization Temp Tc (°C)	100-120	120-155
Density (g/cm3)	1.248	1.335
Thermal Expansion Coefficient x 10-6 (°C –1)	69	69
Melting temperature Tm (◦C)	165	245

Table 1: Properties of Amorphous PLA and PET [10]

6 ANALYSIS OF RESULTS

The energy consumed, per bottle, during the thermal stages of the SMB process is summarised in Table 2. The thermal energy required for one PET bottle uses 2.65kJ whilst one PLA bottle requires 1.96kJ, and therefore the thermal energy saving of 0.69kJ per bottle. This indicates that the energy consumed, per bottle, during the thermal stages of the process when using PLA was 26% less than that used for PET. Thus, a total annual energy saving of 690,000kJ can be achieved in the production scenario of one million bottles per year.

Stretch Blow-Moulding for Bottle Manufacture	**Heating of the Pre-form**
Material Type	*Equation:* $\mathbf{E_{mold} = M_{mold}C(T_{melt} - T_{ambient})}$ 1 Calorie = 4.187 Joules
PET	E_{mold} = 24 x 0.44 x (85-25) = 24 x 0.44 x (60) = 634 calories or 2.65kJ
PLA	E_{mold} = 24 x 0.39 x (75-25) = 24 x 0.39 x (50) = 468 calories or 1.96kJ

Table 2: Calculations of PET and PLA pre-form heating energy usage per bottle during the Stretch Blow-Moulding manufacturing process.

Using the example of 1 million bottles per year, the total number of rejects for PLA bottles based on the wastage levels of 1.5 % will be 15,000 compared to only 5,000 for PET based on its wastage levels of 0.5 %: To calculate the total energy lost through the production of reject bottles, it is assumed that the thermal process considered in this case study will only account for 25% of the total energy required to produce a PET bottle.

Therefore the total energy required to produce a PET bottle is:

(4 * 2.65kJ)= 10.6kJ

Similarly the total energy required to produce a PLA bottle is:

((10.6kJ-2.65kJ) + 1.96kJ) = 9.91kJ

The total energy lost from the PET reject bottles is:

10.6kJ * 5000 = 53,000kJ

Similarly, the total energy lost from the PLA reject bottles is:

9.91kJ * 15000 = 148,650kJ

This gives an additional energy loss of 95,650kj from PLA reject bottles. Therefore in this production scenario a net annual energy saving of 594,350 kJ will be achieved. Assuming the PET bottle reject rate remained at 0.5%, the reject rate for PLA bottles would have to exceed 7.5% to offset the energy savings made from lower processing temperature.

7 CONCLUDING DISCUSSIONS

The scarcity of resources and the rapid depletion of non-renewable provide some of the greatest challenges facing the manufacturing industry in the future. In this context, the substitution of non-renewable materials with renewable ones has been proposed as a possible solution in a number of applications. However, at present there are two major concerns with this solution:

a) the additional demand for renewable materials may compete with other essential requirements, for example the impact of the rapid increase in bio-fuel and bio-materials demands on the food production capacity;

b) the perceived environmental benefits of renewable materials may be offset by the concerns over their overall life cycle impact in particular during the manufacturing, use and end-of-life stages.

In this paper one such concern related to the wider green credentials of bio-polymers, in particular during the production stage, has been assessed. The results of the case study presented in the paper demonstrate that in a comparative study of a typical packing product using PLA and PET, the reduction in energy consumption during the production process using PLA could theoretically be offset by an increase in the number of rejects due its greater sensitivity to temperature variation. In practice however, normal reject rates would be well below the levels necessary for this to occur. Whilst the indications are that bio-polymers have the potential to reduce the environmental impact of plastics packaging at various stages of the life cycle, including the packaging conversion stage, a more detailed and complete life cycle assessment should be carried out for each to ensure that these benefits can be robustly defended.

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Appendix 5

Journal Paper – IJSE 2012

Introduction

This paper has been published in the International Journal of Sustainable Engineering in 2012. For copyright reasons, the version provided in this thesis is incomplete and not the final version which was published.

Bio-plastics in the context of competing demands on agricultural land in 2050

Recent trends in the bio-plastics industry indicate a rapid shift towards the use of bio-derived conventional plastics such as polyethylene (bio-PE). Whereas historically a significant driver for bio-plastics development has been their biodegradability, the adoption of plastics such as bio-PE is driven by the renewability of the raw materials from which they are produced. The production of these renewable resources requires the use of agricultural land, which is limited in its availability. Land is also an essential requirement for food production and is becoming increasingly important for fuel production.

The research presented in this paper envisages a situation, in the year 2050, where all plastics and liquid fuels are produced from renewable resources. Through the development of different consumption and productivity scenarios, projected using current and historic data, the feasibility of meeting global demands for food, liquid fuels and plastics is investigated, based on total agricultural land availability. A range of results, comparing low to high consumption with low to high productivity, are reported. However, it is from the analysis of the mid-point scenario combinations, where consumption and productivity are both moderate, that the most significant conclusions can be drawn. It is clear that while bio-plastics offer attractive opportunities for the use of renewable materials, development activities to 2050 should continue to focus on the search for alternative feed stocks which do not compete with food production, and should prioritise the efficient use of materials through good design and effective end-of-life management.

Keywords: bio-plastics; land use; biomass materials; sustainable materials; managing use and consumption

(1) 1 Introduction

Although the first synthetic plastic material was unveiled in 1862, it was the discovery and subsequent commercialisation of polyethylene in the 1930s which triggered rapid growth in plastics use (American Chemistry Council 2010). In 2008, global production of plastics was around 245 million tonnes with the most significant end uses being in packaging (38%) and construction (21%). Almost half of total plastic consumed takes the form of polyethylene (PE) and polypropylene (PP) (PlasticsEurope 2009). Plastics are typically made from hydrocarbon monomers: products obtained from the cracking of crude oil and natural gas. Estimates state that the production of plastics accounts for around 4-5 % of total crude oil consumption (Queiroz and Collares-Queiroz 2009).

1.1 The role of plastics in a sustainable society

The role of plastics in a sustainable society is often held in question. The non-renewable nature of fossil fuel feed stocks, and the persistence of plastics waste in the environment, present a negative image in terms of resource consumption and end-of-life management. In addition, the primary application of plastics is in packaging, which as a highly visible and high volume waste stream has become almost symbolic of our consumer society's perceived excesses and wastefulness. The reality, however, is more complex. Plastics often offer many benefits over alternative materials, with versatility, low weight and high durability being distinctive characteristics. In particular, plastics packaging can help reduce emissions from transportation of food by weight reduction, and offers the potential for substantial reduction in food waste (Advisory Committee on Packaging 2008). The thermoplastic nature of the majority of polymers used in packaging means that recycling can be readily achieved, with 54% of post-consumer plastics being directed to energy recovery and recycling operations in Europe in 2009 (PlasticsEurope 2010).

1.2 The development of bio-derived plastics

Biopolymers or bio-derived plastics (BDPs) are polymeric materials which, in contrast to conventional plastics, are produced from renewable resources. Some of the first plastics were manufactured from cellulose, but it has only been within recent decades that a real drive to develop new BDPs has emerged.

Initial efforts concentrated on the development of plastics which were both bio-derived and biodegradable. Biodegradable plastics offer potential for alternative end-of-life management processing (Song *et al.* 2009), including the recovery of soil nutrients through composting or the recovery of nutrients and energy through anaerobic digestion. Perhaps the most commercially advanced biodegradable BDP is polylactic acid (PLA), derived from starch. PLA has similar properties to PET (Auras *et al.* 2006) and finds commercial application in a range of packaging types, including bottles, trays and clamshells (NatureWorks LLC 2011). Other biodegradable BDPs include thermoplastic starch (TPS) and polyhydroxyalkanoates (PHA). While significant interest has been demonstrated for application of these materials in packaging, BDPs are also suitable for higher value applications including electrical and electronic equipment and within the automotive industry. Although promising, these materials are still immature in their development, such that their performance and cost have limited commercial uptake (Shen *et al*. 2009; Crank *et al.* 2005).

More recently, a growing range of conventional polymers are being produced (in full or in part) from ethylene, derived from bio-ethanol. These polymers include bio-derived polyethylene (BD-PE), bio-derived polyethylene terephthalate (BD-PET) and bio-derived polypropylene (BD-PP). These bio-derived plastics are functionally identical to their fossil-derived counterparts, and so are compatible with existing manufacturing and recycling processes. Figure 1 shows the global growth in capacity for the manufacture of BDPs in recent years, and illustrates a growing trend in the uptake of these non-biodegradable BDPs (Colwill *et al.* 2009).

• *1.3 Demands and constraints on renewable resources*

The data presented in Figure 1 illustrate an increasing emphasis on renewability as opposed to biodegradability with regard to the development of BDPs. However, the benefits of renewability are only realized for as long as the supply of renewable resources required for BDP production exceeds demand. Increasingly, emphasis is being placed on the use of crop-based materials as alternatives to fossil fuels across a range of applications, including for the production of bio-ethanol and bio-diesel as liquid fuels for transportation.

Concerns over competing demands on agricultural land have led to various studies on the impacts of bio-fuel production on food supplies (e.g. Escobar *et al.* 2009; Harvey and Pilgrim 2011; Ajanovic 2010; Rathman *et al*. 2010; Van der Horst and Vermeylen 2010; Cai *et al.* 2011). Evidence of localised price increases for agricultural land as a direct result of the introduction of energy-crops is cited by eleven authors in a review conducted by Rathman *et al.* (2010). However, the review reports that a similar number of studies dispel the idea of food and fuel crops being in competition for land resources. The majority of studies in this area are concerned primarily with bio-fuel production, and few consider within their scope the production of additional products (i.e. plastics) from these renewable resources. A common feature of all futuristic studies is the uncertainty which lies within projections of human consumption patterns and land productivity (Wolf *et al*. 2003; Gerbens-Leened and Nonhebel 2002).

(2) 2 Research aim and methodology

The primary aim of the research presented in this paper is to investigate the availability of land for the production of BDPs in a future scenario where fossil fuel resources have been exhausted. Although it is unrealistic to suggest that this scenario will be fully realised by 2050, it is generally accepted that within this timeframe oil and gas resources will become seriously constrained (Shafiee and Topal 2009; WWF 2010). We therefore examine an extreme situation, where all plastics and liquid fuels (petrol and diesel) are produced from agricultural crops. In addition, we assume that the land available must also support food production. Production of fuel for stationary power generation is not considered in our research, based on an assumption that existing technologies, including nuclear and renewable energy, will be available as alternatives to biomass-based technologies.

In order to conduct the research, three consumption scenarios have been developed based on projected requirements for the year 2050. In Section 3 we identify the key parameters used to define these scenarios, which include global population, food requirements, liquid fuel requirements and demand for plastics. Historic trends are used to project consumption patterns to 2050. In addition, parameters affecting productivity, namely land availability and agricultural yields, are identified and evaluated. The data developed in Section 3 are used to define a range of scenarios for consumption and productivity which are in turn used to address the primary research aim. HIGH, MID and LOW consumption scenarios are defined in Section 4, covering a range of possible situations for the year 2050. In addition, HIGH, MID and LOW scenarios are defined for productivity based on a range of possible average crop yields for the year 2050. Section 5 presents the results generated from analysis of these scenarios. Total land requirements to support the production of food, liquid fuels and plastics are evaluated for each of the productivity scenarios, in combination with the HIGH, MID and LOW consumption projections. These values are compared with total land availability in order to demonstrate the feasibility of substituting the use of fossil fuel resources with renewable crops for these applications. The discussion of the results generated from the analysis includes identification of significant factors which, although outside the scope of the research presented in this paper, will also impact upon land availability and productivity. Finally, some research conclusions are presented in Section 6.

(3) 3 Evaluation of key parameters to support scenario definition

Consumption and productivity scenarios, defined in Section 4, have been developed based on historic trends and existing data for global population, human food requirements, demand for liquid fuels and plastics, land availability and agricultural yields. These data were used to generate projections to the year 2050, as described in Sections 3.1 – 3.5.

• *3.1 Global population*

Global population is one of the main factors that will impact the demand for resources in the future. The projections used to estimate global population in 2050 were based on statistics for the years 2002 and 2008 (Central Intelligence Agency 2002 and 2008) Using three alternative growth scenarios, high, low and mid range projections were calculated, and are shown in Figure 2.

The mid range projection was calculated, based on the percentage growth in population for the period 2002 to 2008. The global average growth rate was calculated to be 7.14% for this six-year period, although the growth rate for individual countries varied considerably. In order to calculate our mid range projection, constant growth rates are assumed to 2050 for all countries having a growth rate equal to or below the global average (7.14%) for the period 2002 to 2008. For countries whose growth from 2002 to 2008 exceeded the global average, a growth rate of 7.14% is assumed for each subsequent six-year period to 2050. This results in a 42% increase in global population between 2008 and 2050.

A low range projection for global population to 2050 was also calculated, based on an extrapolation of the growth rate for the period 2002 to 2008. In this projection the basic growth rate for an individual country over a six-year period is capped at 20%. Using this basic growth rate, additional factors are incorporated for each six-year period in order to represent a steady decline in growth rate, with global population peaking around 2030. Following 2030 the global population enters a period of gradual decline. These assumptions are consistent with theories presented in the literature (United Nations 2004). In this projection, the global population in 2050 is estimated to be around 7.5 billion, which represents an increase of 10% from 2008.

Similarly, a high range projection for global population was calculated. In this projection countries' individual growth rates for 2002 to 2008 were assumed to remain constant. Only countries with a growth rate greater than 40% had their projected growth rate reduced to 20% for every six-year period. These countries were identified in general as being young economies with populations in 2008 of below 5 million people.

Whilst the general consensus of opinion leans towards a gradual slowdown in the rate of global population growth, there are other more polarized views that predict either a population collapse to around 2 billion people (Duncan 2001) or a continued acceleration in growth driven mainly by developing countries which could see world population reach 13 billion by 2050 (Dahl 2010). The high and low figures used in our calculations are more conservative and in line with more widely accepted worst and best case scenarios, as shown in Figure 2.

- ***3.2 Food requirements***

In order to calculate the food requirement of the population in 2050, we must consider two key factors: population size (discussed in Section 3.1) and population diet. It is common practice in studies of this nature to express the wide variety of foodstuffs that make up the human diet in a single unit of measure. Considering the diversity of animal and plant based materials produced globally and the wide range of farming methods used, there will always be limitations whatever system is employed. For the purposes of this research, it was decided that a physical measure such as kg wheat-equivalent (Nonhebel 2005) or grain equivalents (Penning de Vries *et al.* 1995) would be more appropriate than less tangible values such as calories or joules.

A simple method for estimating the average global diet was followed, based on three diet types described by Penning de Vries *et al.* (1995) and expressed in grain equivalents (GE). These are: Vegetarian (low GE), Moderate (mid GE), and Affluent (high GE). The diet types reflect both the amount and type of food consumed. The Vegetarian diet describes an ample and healthy diet of grains, tubers, crops and pulses with some milk. The Moderate diet includes a small amount of meat and dairy produce similar to that of Japan or Italy, whilst the Affluent diet is found in rich societies, such as the USA, and includes food for pets. Our projections to 2050 assume values for average annual food requirement per capita shown in Table 1. These average values present an image of an equitable society, where food is equally distributed. In reality, it is likely that current inequalities will persist.

These values are a simplistic reflection of food consumption based around primary food types; meat, dairy and plant. They do not take into account the resources required for the subsequent distribution and processing of food, wastage and spoilage levels or the production of beverages and luxury goods.

• *3.3 Demand for liquid fuels*

While coal and gas are mainly used for heat and power generation, the majority of crude oil is used in liquid fuels for transportation (Energy Information Administration 2011). In our research, it was assumed that existing alternative technologies, such as nuclear, solar, wind or wave power, could be used to generate sufficient stationary power to meet human demand in 2050. Transport fuels such as diesel and petrol are highly concentrated forms of relatively safe portable energy for which a large infrastructure and support system exists. Here bio-fuels offer a viable alternative at present as they allow for continued use of existing products and infrastructure, in contrast to, for example, electric cars (Dufey 2006). Ethanol is already added to petrol in many countries at levels of around 2-3%, however national targets seek to increase this to as much as 10% by 2020 (Dufey 2006). Fuel blends containing up to 85% ethanol are currently available for use in specially designed vehicles (Corts, 2010). The two liquid fuel groups, diesel and petrol, are considered separately, as different crops are used in their manufacture. Biodiesel is produced from oil crops and bio-ethanol from sugar/starch crops. In the scenario analysis for 2050 it is assumed that bio-ethanol replaces petrol and biodiesel replaces diesel. Figure 3 shows current and future demand trends for these two fuel groups. Three consumption projections for 2050 were used to give a high, mid and low figure. These were calculated based on data from the Organisation of the Petroleum Exporting Countries (OPEC) for projected oil consumption to 2030 (OPEC 2009). For the low projection, continued growth in line with OPEC estimates is assumed until 2020, at which point further growth ceases. The mid projection follows OPEC estimates to 2030 and extrapolates this growth rate to 2050. These OPEC estimates reflect the slow-down in growth which has occurred since 2008. The high projection uses historic data (Energy Information Authority 2009) to calculate the higher growth rate experienced prior to the recession in late 2008. This higher rate of growth was applied from 2010 to 2050 based on the assumption that growth returns to pre-2008 levels and that supply will keep pace with increased demand.

• 3.4 *Demand for plastic*

The demand for plastics has increased annually since the 1950s. Three consumption estimates for 2050, high, mid and low, were calculated (Figure 4) based on historic data for world production of plastics from 1950 to 2005 (PlasticsEurope 2009). The low projection assumes continued growth at a rate of 4.3% for every five-year period, in line with the level of growth observed between 2005 and 2009. This low growth rate follows the fall in demand during the recession of 2008 and 2009, offset in part by the rise in demand during the rest of this five-year period. The mid range projection assumes a growth rate of 14% every five years, based on the average growth rate observed between 2000 and 2010. The high range projection uses a five-year growth rate of 23% which was calculated as the average growth observed for each five-year period from 1990 to 2010.

Our projections for plastics consumption to 2050 are inclusive of all plastics currently in use. The two main families of plastics are termed thermoplastics and thermosets, of which thermoplastics accounts for the largest share. The substitution of the current range and diversity of polymers in use with an equivalent BDP is a complex scenario. The research simply assumes that a range of BDPs will be available to meet the technical requirements in 2050. Bio-PE was identified as a representative BDP on which to base calculations for land requirements to support plastics production. PE in its various forms; High Density (HDPE), Low Density (LDPE) and Linear Low Density (LLDPE) is currently the largest and most widely used polymer. Given trends identified in Figure 1, it also seemed reasonable to select bio-PE as a reference. In the discussion of yields (Section 3.6) we describe the land requirements for bio-PE in the context of other BDPs, and further justify this approach.

● 3.5 *Land availability*

The production of food is the largest industrial use of both land and water (Wallace 2000; Naylor *et al.* 2005; Gerbens-Leened 2002), yet the land available that is suitable for food production is limited. Of the 30% of the earth that is not under water, only around 31% is suitable for arable crops and 33% for grazing (Penning de Vries *et al.* 1995). Other estimates suggest that less than half of the world’s land area (3000 million hectares) is suitable for agricultural use, which includes grazing, with the majority of this productive land already in use. Further expansion would be limited at the most to around 500 million hectares and this would be achievable only through deforestation (Kindall *et al*. 1994).

For the purposes of this research, land availability data were based on statistics available from the United Nations (Food and Agricultural Organisation of the United Nations 2011). Three classes of land were identified as being potentially available for growing crops, suitable for food, bio-fuel and/or BDP production. These were “crop land” (including all arable land and permanent crops), “grazing land” (including all permanent meadows and pastures) and “forest land”. By plotting global land use statistics from 1950 to 2010, it was observed that in comparison with population growth during the same period, the increase in cultivated land use through gradual deforestation has been modest (Figure 5). It was therefore decided that current land use data would be used to reflect land availability in 2050.

- ### *3.6 Agricultural yields*

The demands on our planet’s resources from its human inhabitants have already exceeded the Earth’s bio capacity by approximately 50%. This overshoot however is largely attributed to the rise in CO_2 emissions, which have grown by twentyfold since 1961, and currently account for over half of this global ecological footprint calculation (WWF 2010). These CO_2 emissions are primarily the result of the rapid increase in the use of fossil fuels, particularly crude oil, during the latter half of the 20th century (Ewing *et al*. 2010). The significance of the increased use of fossil fuels to agricultural yields can be realised when one considers that since the 1950s the area of land use for agriculture, such as the growing of cereal crops, has remained relatively constant, whilst the human population has more than doubled (Figure 5). Whilst a number of factors have contributed to the success in raising agricultural yields, the increased use of fossil fuels has been significant in making current intensive farming practises possible. As land is ultimately a finite resource, improving yields is the most obvious means of meeting increased demand.

Yields can vary significantly depending on the quality of the land, type of farming practice, water availability, additional fertiliser used, climate and type of crops grown etc. In some areas (e.g. the tropics) up to three harvests per year can be achieved. Using a standard measure of Grain Equivalents (GE), yields can vary from under 1 tonne per ha per year in developing countries to over 9 tonnes per ha in the USA and Brazil. In 2010 the global average was around 4.6 tonnes per ha per year. Although a single Grain Equivalent figure can provide a useful standard for making comparisons between global consumption and production levels, it can be misleading when comparing different land and crop types. To avoid over-simplification high, mid and low yield scenarios for each of the key resource groupshave been developed and comprise: food, liquid fuels and plastics. The base data used for these yield scenarios was tailored to each resource group and reflect the crop and land types that would be used.

3.6.1 Food yields

For food, actual yield statistics for cereal production in 2009 were used (Food and Agricultural Organisation of the United Nations 2011). The mid yield figure took the global average for this year; the high yield value took the average for the USA; and the low yield value took the average for India. Achieving average USA yields at global level might appear to be an overly optimistic projection for 2050, even for the high yield value. However, when considering the historic trend in increased yields over the past 50 years (Figure 5), it may not be unreasonable to use this projection. The low yield figure used India as representing a range of agriculture systems, land types, crops and climates. It is not excessively low and reasonable as a low global figure when considering the potential impact of using less productive land, water shortages, fertiliser and fuel limitations and the possible effects of climate change.

3.6.2 Liquid fuel yields

Liquid fuels calculated biodiesel and bio-ethanol separately due to the variation in yields achieved from the different types of crops used in their manufacture. The mid, low and high values are based on actual 2009 average yields achieved in litres per m^2 for ethanol and bio-diesel (Sanderson 2006; Singh *et al*. 2011).

For bio-diesel, the low yield figure is based on average yields from rapeseed crops. The high yield figure is based on production of bio-diesel from jatropha. The mid yield value was calculated as the average of these two extremes.

For bio-ethanol, the low yield value is based on corn as the feedstock using the lower end of the data range reported in the literature. For the high yield value, data representative of bio-ethanol produced from sugar cane and switch grass are used, taking the average of the higher values reported. The mid yield value is taken as the mid-point between the high and low yield values and compares closely with the average yields obtained from switch grass, the high end of corn and the low end of sugarcane.

3.6.3 Plastics yields

The low, mid and high yield values for the production of BDPs are based on current production data for bio-PE from ethanol. Low, mid and high yield values for bio-ethanol production (Section 3.6.2) were combined with a PE yield of 1 kg from 2.3

litres of ethanol (Braskem 2010). This provided a yield, expressed in terms of kg BDP produced, per m^2 of land.

In terms of the production of BDPs in general, bio-PE was identified as being relatively resource inefficient. For comparison, current production figures indicate that 4 kg of wheat starch will produce approximately 2.9 kg of PLA but only 1.1 kg of PE (Siebourg and Schanssema 2008). Given that it is not possible to accurately predict which BDPs and what percentages of each will contribute to total plastics demand in 2050, it was decided that to select the more resource-demanding PE would provide a "worst case" view of land requirements. This decision was also underpinned by the data shown in Figure 1 which indicates the relative growth of non-degradable BDPs compared with biodegradable BDPs. In terms of material substitution, PE is the dominant polymer type currently in use and it is known that bio-PE can substitute conventional PE without any loss in performance during processing, use and at end-of-life.

(4) 4 Scenario definition

Based on the projected data described in Section 3, a range of scenarios have been developed in order to explore future land availability for the production of plastics in a renewable-based society.

Three consumption scenarios are defined in Table 1. The parameters defined for each scenario are global population, food requirements and demand for liquid fuel and plastic. Food requirement is defined per capita, while projections for liquid fuel and plastic are based on data for total global demand. All data are defined for the year 2050. The three consumption scenarios defined in the research are:

LOW consumption

In the LOW consumption scenario, global population growth peaks at 2030 and then declines slowly to 2050. The average diet is low in animal produce and high in grain. Total global demand for liquid fuel has remained at present-day levels, reflecting increasingly prohibitive costs associated with motoring and increasing availability of alternative and more efficient transportation technologies. Demand for plastic has shown only marginal growth, as a result of poor economic growth and/or improved material efficiencies through good design and effective use of recycling.

MID consumption

In the MID consumption scenario, the global population continues to grow at current rates to 2050. Average eating habits include more animal produce than in the LOW consumption scenario, reflecting economic growth in the developing world. Demand for liquid fuel has also continued to grow at current rates, with increased demand from the developing world counterbalanced with improved efficiencies and the adoption of alternative technologies in transportation by developed countries. Growth in plastic useage has also been moderate.

HIGH consumption

In the HIGH consumption scenario, the rate of population growth to 2050 has been increasing more dramatically than in the MID consumption scenario. Economic growth in developing countries is reflected in a spread of consumerism and the adoption of western lifestyles. This has resulted in an increased level of animal produce in the average diet, increased demand for liquid fuel and escalated demand for plastic. Sustainability concerns have had little impact on consumption patterns.

Whereas consumption scenarios are used to identify potential demands on land in 2050, the availability of renewable resources is defined by productivity scenarios. Based on the data explored in Section 3, the amount of land available is assumed to remain constant for the LOW, MID and HIGH productivity scenarios. Average agricultural yield varies for each scenario, as described below:

LOW productivity

The LOW productivity scenario in 2050 is defined by poor yields, which are lower than the average global yields achieved today. This scenario could arise as a result of exhaustion of previously productive agricultural land and reduced availability of fertilizers. Intensive farming practices have been slow to spread to the developing world and unpredictable weather patterns have had localized catastrophic impacts on crops

MID productivity

The MID productivity scenario in 2050 is defined by moderate yields, achieved through a maintenance of current farming standards. Increased yields from the spread of intensive farming practices are counter-balanced by exhaustion of land in over-cultivated areas.

HIGH productivity

The HIGH productivity scenario in 2050 is defined by high yields, above current average values, achieved through a mixture of good land management, effective crop selection and improvements in agricultural practice. Developing countries adopt more intensive farming practices, with increased use of fertilizers and mechanised processes.

(5) 5 Scenario analysis and discussion

The scenarios developed in Section 4 have been used to investigate the feasibility of meeting global demand for plastic entirely from the use of agricultural crops, thus competing with the production of food and liquid fuel. Sections 5.1, 5.2 and 5.3 present the results generated based on the HIGH, MID and LOW productivity scenarios defined in Table 2. In each section, calculated total land requirements to support the LOW, MID and HIGH consumption scenarios are presented and compared with total land availability. Section 5.4 presents a discussion of the validity of the results generated, identifying some limitations to the current research.

• *5.1 HIGH productivity scenario analysis*

The total land requirement to support human demand for food, liquid fuels and plastics was calculated for each consumption scenario defined in Table 1, using the HIGH productivity scenario defined in Table 2. The assumption is that the total demand for petrol and diesel fuels are met by bio-ethanol and bio-diesel respectively, and the total demand for plastics is met by BDPs. The results from these calculations are shown in Figure 6. Total land availability is shown for comparison.

This set of results indicate that in a HIGH productivity scenario, it is feasible that human demands for liquid fuels and plastics could be met using renewable raw materials, without significant threat to food production. Even for the HIGH consumption scenario, the majority of food requirements could be met using crop land, with some food requirements being met by the use of grazing land for the production of meat and dairy. A portion of crop land would therefore remain available for the production of liquid fuels and plastics, with the remaining demand for liquid fuels and plastics being met by grassy crops grown on grazing land. The total land requirement for plastic production is between 5% and 7.5% of the total land required to support these competing end uses.

The combination of low consumption and high productivity shown in Figure 6 is indicative of the “best case” scenario developed in the research. This scenario assumes low global population and a radical shift in average human behaviour towards a diet which is low in animal produce, and demand for liquid fuel and material similar to current consumption rates. In addition, the yield assumed for the HIGH productivity scenario is in line with current yields in the most advanced farming communities.

• *5.2 MID productivity scenario analysis*

Figure 7 shows the total land requirements for LOW, MID and HIGH consumption scenarios in combination with the moderate yields defined in the MID productivity scenario. It can be seen from the results that even for the LOW consumption scenario, demand for land exceeds the available crop land and utilises almost half of available grazing land. The total land requirement for the MID consumption scenario is similar to the total land requirement for the HIGH consumption scenario in combination with HIGH productivity (Figure 6). For the MID consumption scenario, the land requirement for food, liquid fuels and plastics totals all available crop and grazing land. For the HIGH consumption scenario, the total land requirement extends to an area as large as all available crop and grazing land, as well as the majority of forest land.

This MID productivity scenario reflects average crop yields achieved today, and as such presents a scenario which could be realistically envisaged. It is likely that some improvements will be made in crop yields in the developing world, and these would counterbalance reductions in crop yields elsewhere in the world through soil degradation and land exhaustion. The results for the MID consumption scenario presented in Figure 7 reflect the mid-point developed in this research, which is possibly the most realistic or likely situation for 2050. The results here suggest that, on the basis of the assumptions adopted in the calculation of land availability, a switch to crops as raw materials for liquid fuel and plastic cannot be dismissed as being totally unfeasible. The total land requirement falls marginally within the total area of crop and grazing land available. This result highlights the importance of effective resource management, in both agricultural production and in consumer behaviour. The results for the HIGH consumption scenario here illustrate the impact of uncontrolled growth in demand for fuel and materials and the effect this would have on the ability with which demands can be met by the use of renewable resources. It is unfeasible to suggest that the complete destruction of forest land to support food, fuel and plastics production provides a sustainable solution to meeting human needs. As well as playing an important role in supporting the planet's ecosystems, forests provide an essential source of wood and charcoal fuels, as well as raw materials for other industrial uses. The results presented in Figure 7 emphasise the importance of decoupling economic growth with increasing consumption: the principal challenge of sustainable development.

• 5.3 *LOW productivity scenario analysis*

Figure 8 shows the LOW productivity scenario and the resulting land requirements for LOW, MID and HIGH consumption scenarios. Low crop yields cause demand for land to significantly exceed available crop land for all three consumption scenarios. For the MID consumption scenario, a large proportion of forest land would be required to meet the human demands considered within the research, and for the HIGH consumption scenario, land requirements could not be met, even supposing all forest land could be cleared and used for agricultural purposes.

The results presented in Figure 8 for the HIGH consumption scenario illustrate the "worst case" developed in this research, in which land availability is not sufficient to meet food requirements, and therefore provides no opportunity for providing crop-type resources for competing markets. As with the "best case" presented in Section 5.1, the likelihood of this "worst case" scenario being realised is low. The low crop yield defined in the low productivity scenario used as the basis of these calculations could only be envisaged as a result of extreme effects from climate change or some other catastrophic occurrence. However, this extreme scenario presents a picture of a situation where consumption patterns remain unchecked and a lack of concern for the environmental impact of human behaviour results in substantial degradation of the planet's resources.

- ### *5.4 Limitations of the scenario analysis*

The scenarios developed in this research, and the results presented in Figures 6, 7 and 8 above, are intended to provide a broad view of the situation regarding the availability of land in terms of providing renewable resources as raw materials for liquid fuel and plastic. The variation in the results presented, from the "best case" to "worst case" scenarios, indicates the complexity of the issue, as well as the sensitivity of the situation to factors such as population growth and crop yields, which are difficult to predict. Some of the issues which have not been directly included within the research, but which are acknowledged as being significant, are identified below.

In defining the consumption scenarios, it has been assumed that the only demands on agricultural land will be food, liquid fuels and plastics. Other significant uses include the growth of tobacco crops and the production of natural fibres, such as cotton, for textiles. Some industrial processes, such as steel production, consume substantial quantities of coal, which in future may need to be substituted. The production of stationary power (e.g. in power stations) has been deliberately excluded from the scope of the research, while in reality there a likelihood that some stationary power will be generated using biomass grown specifically for that purpose. As the global population grows, it may also be that some agricultural land area is lost to the construction of roads and homes. Furthermore, the use of forest land for solid fuel production (wood and charcoal) and other industrial purposes has not been incorporated in our considerations with respect to future projections.

We have also based our projected consumption requirements on historic and current human behaviours. In reality, it is understood that human behaviour changes over time, and adjusts in particular to economic and social factors. While the consumption scenarios developed in the research encompass a range of potential situations for the year 2050, we are not able to predict step-changes in human behaviour which could radically change demand for liquid fuels and/or plastics.

In defining the productivity scenarios, we have taken a rather simplistic approach in developing average crop yields based on data reported in the literature. In reality, agriculture is heavily dependent on a complex list of factors, including water availability, climate, weather patterns and the availability of fertilisers, machinery and other infrastructure required to support farming. In particular, the availability of clean drinking water is essential for human survival, and the redistribution of water for irrigation can have catastrophic impacts on local communities. In our research we have made the assumption that sufficient water is available to agricultural land. This assumption is unlikely to reflect the real situation in 2050. The nature of agriculture is such that the production of renewable resources is closely linked with the weather and the climate. Global changes in climate have the potential to substantially change agricultural yields, as well as presenting the possibility of rising sea levels and the consequent loss of low-lying arable land. Extreme weather conditions, such as droughts, hurricanes and floods, can have catastrophic impacts on farming and these perhaps take on even greater significance as land availability is stretched. Even without such extreme events, the production of raw materials from agriculture, where availability is so closely linked with the seasons and fluctuations in weather, is characteristically different from the relatively constant business of extracting fossil fuels. The resulting impacts on trade and economic behaviour have not been considered in this research.

On a more positive note, it is possible that alternative sources of raw materials may be developed to support the production of liquid fuels and plastic. Already, a shift towards the use of cellulosic materials, rather than sugars and starches, is planned for both product types. Research into the use of algae to produce biomass is promising, and although farming this resource from the sea may introduce its own environmental problems, there is potential to reduce the strain on land and remove competition for food production. Similarly, opportunities to utilise the resources available from waste have the potential to alleviate the requirement of growing “virgin” crops as raw materials for fuels and/or plastics production.

Finally, we have conducted a theoretical analysis in which global demand has been compared against global supply. In reality, perhaps the biggest challenge associated with food production is not the growth of sufficient crops, but rather the distribution of food to the people who need it. Today, despite there being more than adequate resources available at the global level, it is estimated that over 1 billion individuals live in poverty and hunger (Food and Agricultural Organisation of the United Nations 2009). Simply demonstrating a theoretical ability to meet global demand by no means indicates that the requirements of the individual will be met. The challenge of distribution relates not only to food, but also to renewable materials required for the production of liquid fuels and plastics. Transportation of these raw materials from agricultural areas to processing plants to the consumer, introduces additional environmental impact and resource demands within the supply chain.

6 Conclusions

The production of plastics from renewable resources at present offers an attractive opportunity for reducing fossil fuel consumption and improving the apparent sustainability of products and packaging. However, in the future, increasing pressure on land for the production of food and liquid fuels will challenge priorities in terms of the allocation of renewable resources. The wide range of scenarios presented in this study illustrates the complexity of the issues involved in predicting human consumption patterns and land productivity in the future. In the worst case (low productivity combined with high consumption), the ability of agricultural land to support human demands is far exceeded, even with the expansion of farming into existing forests. In the best case (high productivity combined with low consumption), human demands could, theoretically, be met with ease. However, these extreme cases represent possible, but unlikely, situations for the future.

The moderate case (mid productivity combined with mid consumption) represents the most likely situation for 2050, and it is from this that the most significant conclusions from the study can be drawn. Here the maximum available crop and grazing land is used in its entirety to support production of food, liquid fuels and plastics. In reality, considering the simplified approach adopted in the scenario development applied in this study, as well as the unavoidable inefficiencies in agricultural, manufacturing and distribution processes, this moderate case does not represent a sustainable solution.

This failure leads us to conclude that although renewable fuels and materials appear attractive today, they do not provide a straightforward global solution which will allow human consumption patterns to remain unchecked. While both plastics and liquid fuels are essential requirements of modern supply chains, and will remain so especially within the context of increased urbanisation and population growth, food production will always remain a priority. This conclusion, developed from an evaluation of global resources and requirements, does not reflect regional variations in local land availability. Regions rich in agricultural land may well be able to support the demands of their local populations into the future. However, as global resources become increasingly constrained, it is debatable whether the priorities of individual countries can remain detached from global pressures.

In terms of the BDP industry, continued emphasis should be placed on the exploration and development of alternative feed stocks for plastics, which do not compete with food production; for example, algae and waste. In addition, improvements in resource efficiency, achieved through the development of efficient recycling processes, innovative design, and changed consumer behaviour, will continue to be essential for sustainable development.

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Table 1. Definition of LOW, MID and HIGH consumption scenarios, based on projections to the year 2050. Food requirement data taken from Penning de Vries *et al*. 1995. Calculation of all other data projections is detailed in Section 3.

		Consumption scenarios 2050		
		LOW	**MID**	**HIGH**
Total global population		8 x 10^{9}	9.5 x 10^{9}	12 x 10^{9}
Food requirement (GE per capita, kg)		475	875	1530
Liquid fuel requirement (total, litres)	Petrol	2.6 x 10^{12}	3.4 x 10^{12}	4.1 x 10^{12}
	Diesel	1.9 x 10^{12}	2.5 x 10^{12}	3.0 x 10^{12}
Plastic requirement (total, kg)		3.4 x 10^{11}	7.0 x 10^{11}	13.0 x 10^{11}

Table 2. Definition of HIGH, MID and LOW productivity scenarios, based on projections to the year 2050. Land availability is assumed to be constant for all scenarios. Calculation of data projections is detailed in Section 3.

	Productivity scenarios 2050		
	HIGH	**MID**	**LOW**
Average agricultural yield (kg GE m^{-2})	0.72	0.35	0.25
Average bio-ethanol yield (l m^{-2})	0.80	0.55	0.30
Average bio-diesel yield (l m^{-2})	0.20	0.15	0.10
Average BDP yield (kg m^{-2})	0.35	0.24	0.13
Total land availability (m^2)		8.7×10^{13}	
Cropland (m^2)		1.6×10^{13}	
Grazing land (m^2)		3.4×10^{13}	
Forest (m^2)		3.8×10^{13}	

Figure 1. Global production capacity for compostable (biodegradable) and non-compostable bio-derived plastics (BDPs) (European Bioplastics 2009)

Figure 2. Projections for global population growth to 2050. High, Mid and Low projections used in the research are plotted against a selection of projections reported in the literature (FAO = Food and Agriculture Organisation of the United Nations 2011; USCB = U.S. Census Bureau 2011; UN 93 = United Nations 2003; UN 98 = United Nations 2008; PAI = Young *et al.* 2009).

Figure 3. Global demand for liquid fuels, projected to 2050. Petrol and diesel account for around 75% of global crude oil demand. Original data sources and projection calculations are detailed in Section 3.

Figure 4. Global demand for plastics, projected to 2050. Original data sources and projection calculations are detailed in Section 3.

Figure 5. Historic data for land use (Food and Agricultural Organisation of the United Nations 2011) in comparison with global population growth, between 1950 and 2010.

Figure 6. Scenario results for LOW, MID and HIGH consumption scenarios in combination with HIGH productivity.

Figure 7. Scenario results for LOW, MID and HIGH consumption scenarios in combination with MID productivity.

Figure 8. Scenario results for LOW, MID and HIGH consumption scenarios in combination with LOW productivity.

Appendix 6

Packaging Specification

Introduction

Example of a plastic bottle packaging specification

EXAMPLE PACKAGING SPECIFICATION - Plastic Bottle

Product description

Type of packaging ☐ *Packaging coming into contact with food*

☐ *Packaging not coming into contact with food*

Intended content - *type of food product*

- *capacity*

Other system components - *closures*

- *inner liner*

- *secondary containers*

- *labels*

Construction/dimensions/layer thickness

Machineability

Filling/packaging conditions

Storage conditions (including packed good) - *intended storage period*

- *storage temperature*

Printing process - *printing inks*

- *printing materials*

Adhesives

Storage conditions for packagings/packaging materials - *palletizing*

- *environment/temperature*

- *periods of use*

Sampling

Agreement on tests - *strengths*

- *vapor/gas permeability*

- *strength of the sealed seam*

- *adhesive properties*

- *migration properties*

Appendix 7

Sustainable Plastics Packaging Checklist

Introduction

Copy of the Sustainable Plastics Packaging Checklist used in Chapter 8

Sustainable Packaging Checklist

This checklist has been developed from published sustainable packaging design checklists and guides. The check list provides a list of the key considerations and their potential impacts that should be considered during the packaging design SBSC process. The information contained in the checklist was derived from a number of published sources which include:

- The Consumer Goods Forum (2011), Global Protocol on Packaging Sustainability 2.0, available online at: www.consumergoodsforum.com
- Woolworths Limited (2011), Packaging Sustainability Guidelines, available online at www.wowlink.com.au/
- Australian Packaging Covenant (2010). Sustainable Packaging Guidelines, available online at: www.packagingcovenant.
- Envirowise 2008, Packguide: a guide to packaging eco-design, available online at: www.envirowise.gov.uk
- Envirowise Guide GG360 (2008), Packaging design for the environment, available online at: http://www.envirowise.gov.uk/GG360
- INCPEN (2003), Responsible Packaging - Code of Practice for optimising packaging and minimising packaging waste, available online at: http://www.incpen.org

The checklist is ordered by life cycle stage and the impacts are considered within that context. Each of the Key considerations includes the relevant SBSC perspective which it is most likely to come under and a brief indication of the potential impacts and strategic relevance likely to be affected by it.

This list is not intended to be extensive and can be added to over time. However the key considerations listed are also accounted for under the relevant key performance indicators, within the database under tier two. This is to ensure that materials can be identified and selected according to their ability to meet the key strategic requirements that are identified using this checklist and which ultimately form part of the sustainable plastics packaging strategic design brief/specification.

Sustainable Plastics Packaging Checklist

Life Cycle Stages	SBSC Perspective(s)	Key Considerations	Potential impacts and strategic relevance
Raw Materials	Non-Market (Environmental)	Finite resources v Renewables	Direct and indirect depletion of finite resources. Unsustainable.
	Non-Market (Social)	Food Competing	Higher food prices, reduced availability – famine/poverty
	Non-Market (Environmental)	Land and water Use	Loss of habitat and bio-diversity, pollution.
	Non-Market (Social)	Land and water Use	Food production, population displacement, drought, health
	Non Market (Environmental)	Emissions	GHG / climate change, air quality, health
	Financial	Purchasing	Cost, stability, availability, choice, delivery
Polymer Production and Pack Conversion	Financial	Energy Use/cost	Total use and peak use
	Internal Process	M/C Compatibility	Set-up, capex, downtime
	Internal Process	Output Efficiency	Speeds, Throughputs
	Non-Market (Environmental	Waste / Emissions	Cost, disposal, resource efficiency
Warehouse	Internal Process	Storage practise	Conditions, risks, handling, space
	Financial	Storage costs	Shelf Life, Insurance costs
	Internal Process	Use	Compatible with existing systems
Manufacturer	Internal Process	Use, time, waste, reject	Competitiveness, margins

Packer/filler	Financial Financial	Unit Cost Supply security,	Competitiveness, margins Price stability, flexibility
Distribution	Internal Process Financial Internal Process Internal Process Financial	Product protection – Damage and losses Distances and mode of transport Cube, weight, damage, returns	Competitiveness and use of natural resources. Deliver efficiency, variable requirements Waste and cost
Retailer	Internal Process Financial	Out of date – shelf life Damage and handling	Consumer satisfaction – Quality and reliability
Consumer	Internal Process Financial	Single use – disposal Cost Performance	Excessive packaging and disposal options. Product - clean, undamaged
EOL	Financial Non Market (Environmental)	Disposal Recyclable Compostable Biodegradable Pollutant -Litter	Producer Pays PRO Waste Hierachy, preservation of materials Unsightly, hazard to wildlife
General	Internal Process Non Market (Environmental)	Side-effect of alternative properties: (bio-degradable, edible)	Consider unique properties – what impact will they have at each stage of the companies processes

Appendix 8

Supporting case study data

Introduction

Sample reference and data used to simulate companies in case study

For copyright reasons only links to the data source are included.

Links to data sources used to develop case study companies

http://www.pepsico.com/download/PEP_Annual_Report_2012.pdf

http://assets.coca-colacompany.com/c4/28/d86e73434193975a768f3500ffae/2012-annual-report-on-form-10-k.pdf

http://www.cokecce.co.uk/media/90796/13759-cce-sb-sustpackaging-final.pdf

http://assets.coca-colacompany.com/a3/cc/09a520d94eb0a69f51ccd8d7b00a/SR08_SusPack_26_29.pdf

http://www.pepsico.com/Download/Global_Pack_Policy.pdf

http://www.cokecce.com/corporate-responsibility-sustainability/sustainable-packaging-and-recycling

http://www.coca-colacompany.com/sustainabilityreport/world/sustainable-packaging.html

http://www.coca-colacompany.com/our-company/mission-vision-values

http://www.article13.com/A13_ContentList.asp?strAction=GetPublication&PNID=1395

http://www.pepsico.com/Download/Global_Pack_Policy.pdf

http://www.packworld.com/machinery/fillingsealing/new-coke-plant-designed-future-mind

http://www2.isye.gatech.edu/~jjb/wh/projects/Coke/main.html

http://www.beverageworld.com/articles/full/14884/coca-cola-amatil-invests-450m-in-blow-fill-technology

http://www.finewaters.com/Water/Health/Shelf_Live_of_Bottled_Water.asp

http://www.norner.no/bcalc/model/otr/bottle#result

http://www2.isye.gatech.edu/~jjb/wh/projects/Coke/main.html

http://www.composite-agency.com/archive/Carbon-Dioxide-Diffusion-PET.pdf

http://www.nextek.org/Data/Presentations/Next_Steps_in_LW_PET_Bottles.pdf

http://www.wrap.org.uk/sites/files/wrap/15624-02%20PET%20Case%20Study%20HiRes%20PPV.pdf