AN EXPLORATION OF CHANGES IN ENVIRONMENTAL SUSTAINABILITY OF PACKAGING, 1971 TO 2011

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ABSTRACT

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This study investigated trends in environmental sustainability of US consumer packaging from 1971 to 2011, comparing twenty-three “current” packages to twenty-three “old” packages.

A Life Cycle Assessment (LCA) methodology, using COMPASS® software was employed. The scope of the LCA in this study includes the manufacturing, the conversion, and the end-of-life phases of the primary packaging. Five life cycle impact indicators were selected in this study: fossil fuel consumption, water consumption, biotic resource consumption, mineral resource consumption, and greenhouse gas (GHG) emissions.

The results show that packages produced by companies in the U.S have become more environmentally sustainable over time. If the old and new packages are made from the newer, same materials, the lighter, package had less environmental impacts. When a glass jar was changed to a steel can, PET, and paperboard carton, the alternatives have less environmental impacts than the glass jar. However, when an EPS clamshell and a steel can were changed to a paperboard clamshell and a rigid plastic container each, the old package had less environmental impact than the current alternatives.

The main contributor to the impact indicators for most packages was the manufacturing phase, because of the extraction of raw material and production of resins. The exceptions to this were the GHG emissions for paperboard cartons and the water, biotic, and mineral consumption for rigid plastic containers.

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LIST OF SYMBOLS or ABBREVIATIONS

LCA: Life cycle assessment

LCI: Life cycle inventory

LCIA: Life cycle impact analysis

MSW: Municipal solid waste

EOL: End of life

GHG: Greenhouse gas

GWP: Global warming potential

CO_2 equi: Carbon dioxide equivalents

PCR: Post-consumer recycled

CRB: Clay-coated Recycled Board

BP: Bleached paper

EPS: Expanded polystyrene

LDPE: Low density polyethylene

HDPE: High density polyethylene

PP: Polypropylene

PET: Polyethylene terephthalate

PLA: Polylactide resin

PS: Polystyrene

PVC: Polyvinyl chloride

CHAPTER 1: INTRODUCTION AND OBJECTIVES

Packaging is an absolute necessity around the world. Most industries need it because of safety, convenience, efficiency, and marketing reasons. At the same time, however, packaging is targeted as one of the largest burdens to the environment. That is to say, packaging is a necessary evil in production-oriented economies since packaging waste is a large proportion of solid waste, while it prevents loss, damage and deterioration and encourages the marketing value of products (Lee et al. 2005). Therefore, many governments and communities have concerns about the packaging industry and have legislated various restrictions and voluntary agreements to minimize packaging waste.

In the past, measuring methods of these restrictions and agreements had a tendency to be developed only around the traditional waste management methods such as reduction, reuse, recycling, and recovery (Sonneveld et al. 2005).

Now, however, the packaging landscape is being driven more by concerns of Carbon Foot Printing and Life Cycle Green House Gas (GHG) emission analysis due to the Kyoto Protocol of 1997, which is an international agreement aimed at reducing global emissions of greenhouse gases. Packaging measurement has changed to more holistic concepts including the entire product lifecycle (Sonneveld et al. 2005). This integrated concept is regarded as sustainability. Following this trend, the measuring methods for environmental impacts of packaging in most policies now focus on packaging material resource consumption per unit of product.

Over the past few decades, many companies have conducted studies to measure and improve the sustainability of their own packaging (Corti et al. 2007). Many major corporations have published reports of sustainability. For example, since the mid-1990s, McDonalds, 3M, UPS, Ball Corporation, Unilever, and Procter & Gamble have annually announced their sustainability reports, to introduce their efforts to make their packaging more environmentally sustainable. Sustainable packaging claims have been adopted as an efficient marketing tool by several companies, because it may reduce the consumer's guilt about environmental pollution as well as help to make a brand's image more responsible and clean. In a Forrester Research survey, 2010, Eighty-five percent of responding corporate technology leaders said they considered environmental concerns "very important" or "important" when they set their company's technology strategy (Mckay 2010).

Therefore, at this point in time, understanding and evaluating packaging sustainability shifts with time can show whether the efforts of society, including governments and industries, have had an impact on increasing packaging sustainability.

Objectives:

This research seeks to understand whether increasing concerns for the environment and awareness of the need for packaging sustainability during the past few decades has affected consumer packaging trends. This information can help to forecast future shifts.

The objective of this study is to investigate the hypothesis that current packaging in 2011 tends to be more environmentally sustainable than past packaging from the 1970s to 2000.

Packages investigated in this study were forty-six samples produced from the 1970s to 2011. Four different material types of packages were selected: paperboard, glass, metal and rigid plastic.

The scope of this study includes the manufacturing phase, the conversion phase, and the end-of-life phase of primary packaging.

The methodology used for investigating environmentally sustainability of packaging in this study is life cycle assessment (LCA), and the software program used for the LCA simulations is COMPASS® (SPC 2010).

It should be noted that packaging sustainability is not necessarily only evaluated by an environmental assessment, and can also involve economic assessment and social assessment. However, in this study, the scope of investigation for sustainability is limited to only environmental life cycle assessment. Therefore, evaluations of economic and social aspects are not dealt with in this study.

CHAPTER 2: BACKGROUND AND LITERATURE REVIEW

This literature review first covers definitions of sustainability, principles of sustainable packaging and the ways sustainability is measured, including LCA. The second half of the literature review explores the history and application of LCA to packaging and introduces the LCA tool, COMPASS, used for this research.

2.1 Packaging sustainability

The activities within a life cycle of a package impact factors related to the environment. One of the greatest impacts is on solid waste. Packaging waste comprised 29.5% of municipal solid waste (MSW) in 2009, down from 36% in 1978. However, over the course of these four decades, the total amount of MSW in the US has doubled, as shown in Figures 1 to 5.

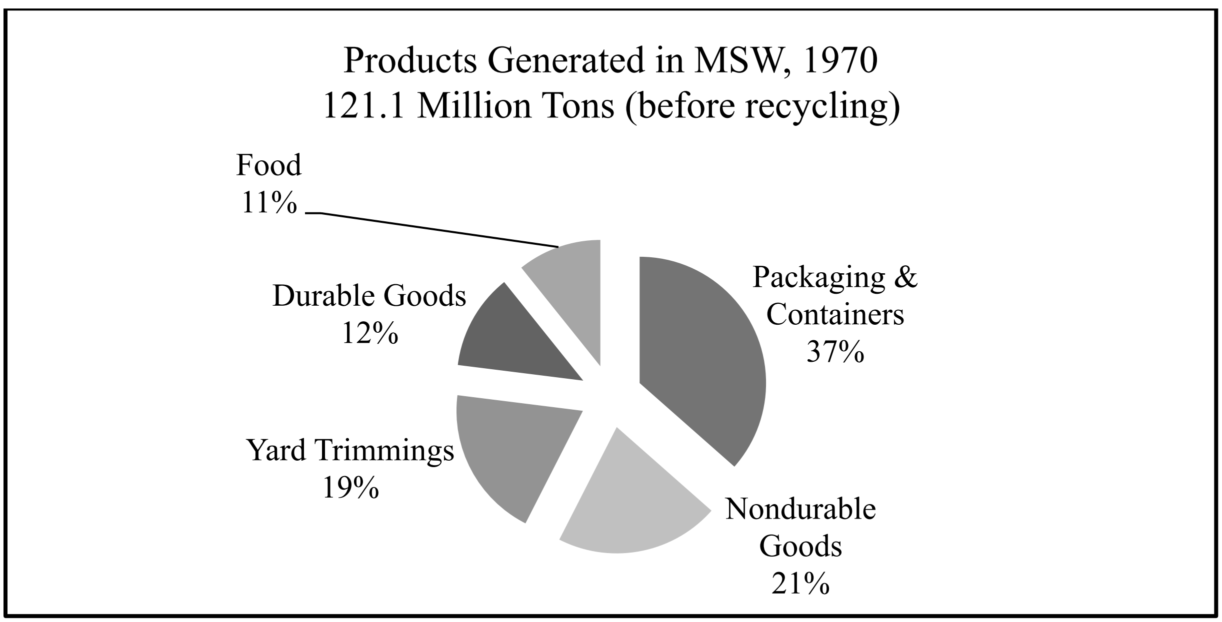

Figure 1 Products Generated in MSW, 1970 (EPA 2002, pg. 81)

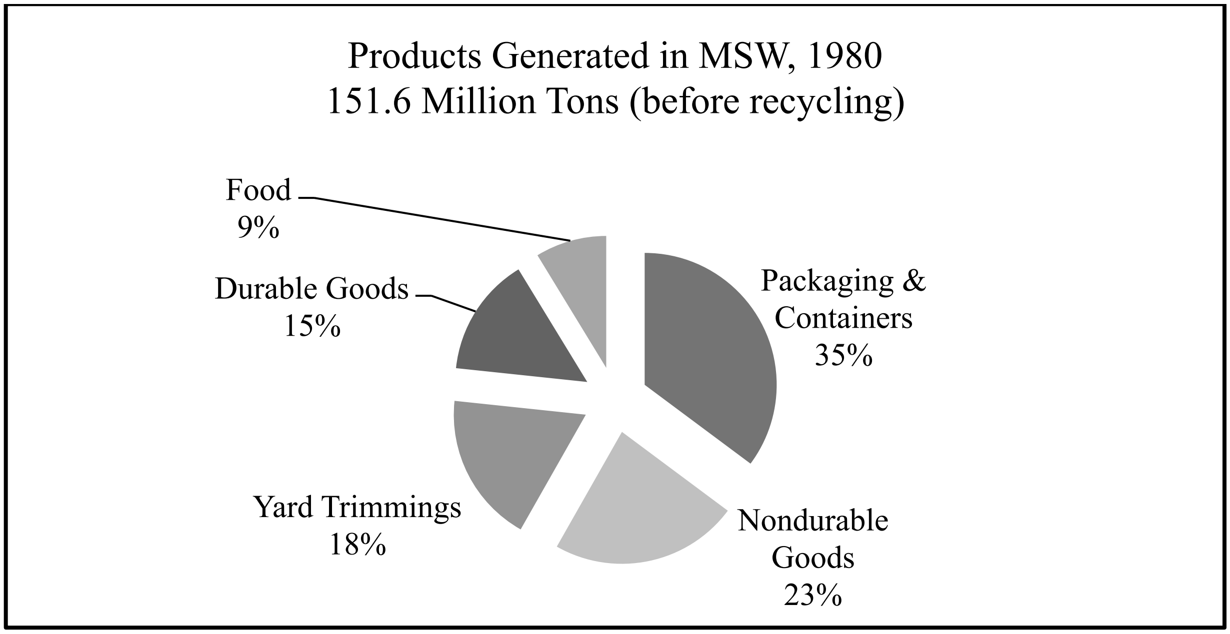

Figure 2 Products Generated in MSW, 1980 (EPA 2002, pg. 81)

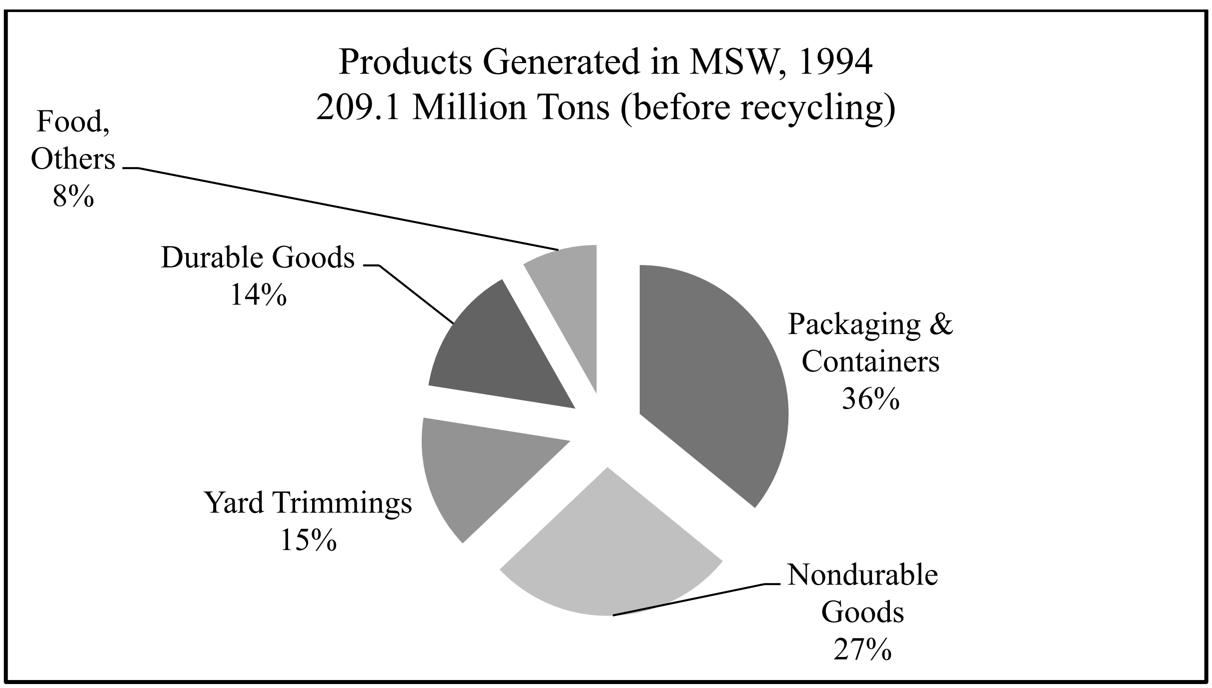

Figure 3 Products Generated in MSW, 1994 (EPA 2002, pg. 81)

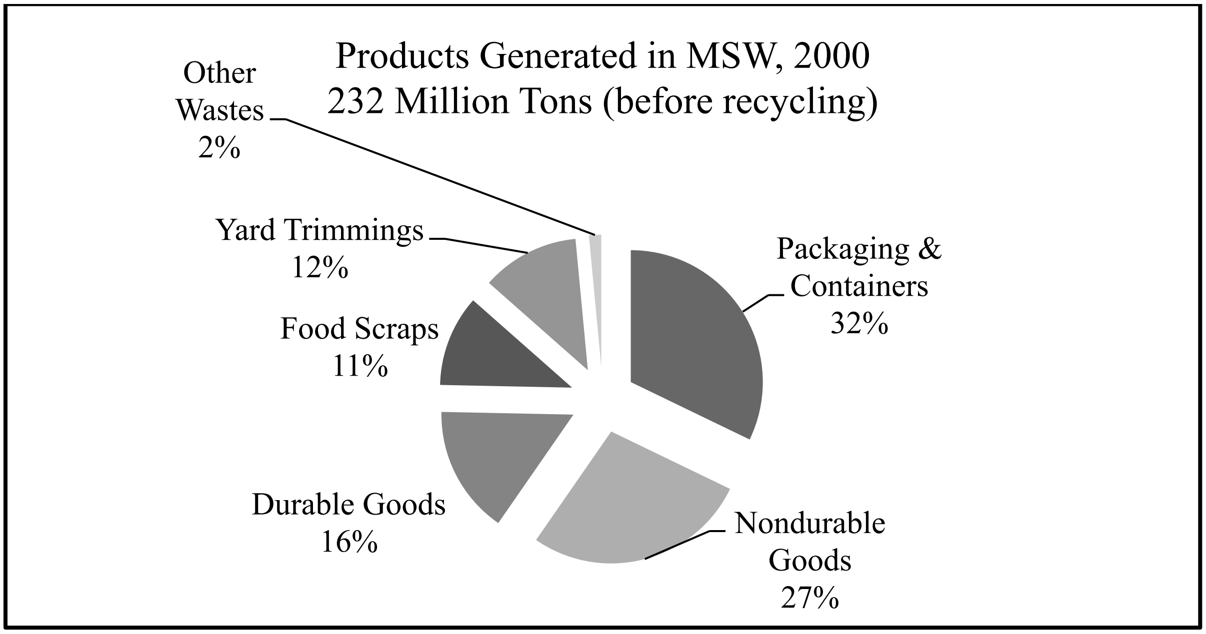

Figure 4 Products Generated in MSW, 2000 (EPA 2002, pg. 8)

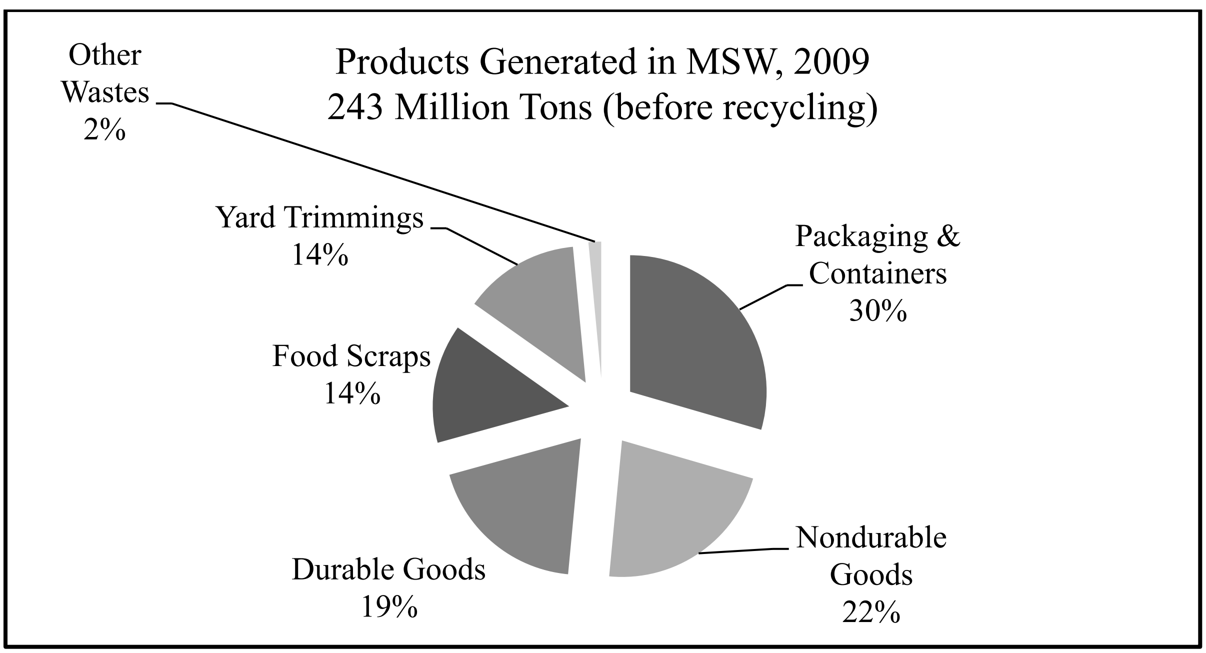

Figure 5 Products Generated in MSW, 2009 (EPA 2010, pg. 72)

Due to concerns about the increasing amount of waste, the packaging industry has been encouraged to minimize packaging waste as well as improve recyclability (Lewis et al. 2007).

Political activities increasingly aim at packaging as a means to cut the amount of waste (Thogersen 1996). The earliest legislation was in Europe.

Today, the concerns about environmental hazards regarding packaging wastes and government initiatives/regulations to reduce greenhouse gas (GHG) emissions are increasing (GIA 2010). Companies around the world have been charged to identify the major environmental impacts of their activities, and change these impacts in their manufacturing system, design, logistics, marketing and business models (Lewis et al. 2007).

2.1.1 Definition of sustainability

"Sustainability" is a term originating from silviculture and adopted by the United Nations Environment Program (UNEP) as a primary political goal for the future development of humankind and product development (Klopffer 2003). The most popular definition of sustainability can be traced to the 1987 UN Conference of Environment and Development as "meeting present needs without compromising the ability of future generations to meet their needs" (WCED 1987, pg. 43).

From an environmental point of view, "sustainable" or "sustainability" is a complex, not precisely defined term, since it is difficult to certainly interpret the environmental damage caused by human activities at personal, corporate and government levels (Lewis et al. 2007). It is also difficult to establish a solid definition of "sustainable packaging" because of the speed with which technology is evolving (Fontaine 2008).

In the past, the term sustainability was often just associated with recycling or recycled material (Brown 2004). So, when asked what makes a packaging system more sustainable, most people continuously offered a one-word answer, 'recycling' (Young 2008). This answer is insufficient since it tends to be pursued without considering the complex roles of packaging and the packaging systems closely related with supply chains (Lewis et al. 2007). In fact, most recycling is actually “down-cycling”, as materials are reused in less valuable applications in each cycle (Brown 2004). Down-cycling means that materials are recycled into a lower value material that will later be thrown away, and does not meet the standard for “highest and best use” (CIWMB 2008). Furthermore, recycling may not cause the most environmentally superior result from a whole lifecycle perspective since pollution, energy and water consumption may also be critical factors (Unilever 2009).

The choice of a sustainable solution needs to consider specific conditions of each case such as manufacturing, supply chains, regulations, and regions. Isolated environmental objectives or methods without considering these conditions limit companies and governments from enhancing their overall environmental performance including economic and social performance. Due to the drawback of the isolated environmental concept, corporations have struggled to integrate their environmental objectives with other business drivers regarding cost, market share and customer expectations, considering their supply chains (Lewis et al. 2007).

Beyond just reducing and recycling, the outcome from this holistic concept is called “packaging sustainability”. Recycling is just one aspect of packaging sustainability (Kralj et al. 2008). The Packaging Council of Australia (PCA) promotes the concept that “a sustainable packaging and product supply chain is a system that enables products to be produced, distributed, used and recovered with minimum environmental impact at lowest social and economic cost”. This might be the ideal definition (Lewis et al. 2007, p. 9).

2.1.2 Principles and functions of sustainable packaging

Organizations for sustainable packaging such as the Sustainable Packaging Coalition (SPC) in the United States and the Sustainable Packaging Alliance (SPA) in Australia have made their efforts to define sustainable packaging by setting up the concepts or principles to help decision-making (Lewis et al. 2007).

The economic, social and environmental functions of packaging are considered in the context of the triple bottom line, which originated by John Elkington, as shown in Figure 6 (Elkington 2004). The economic/commercial functions mean packaging fulfills such demands as transport, protection, and shelf life. The social functions mean packaging for social benefit such as safety and convenience. The environmental functions mean minimizing environmental impacts of packaging such as global warming impacts and solid wastes (Lewis et al. 2005). Among them, the social function is the most difficult to quantify in a meaningful way. Examples of social issues are protection of workers and their families' health, the right to collective bargaining, and avoiding the use of forced or child labor (Svanes et al. 2010).

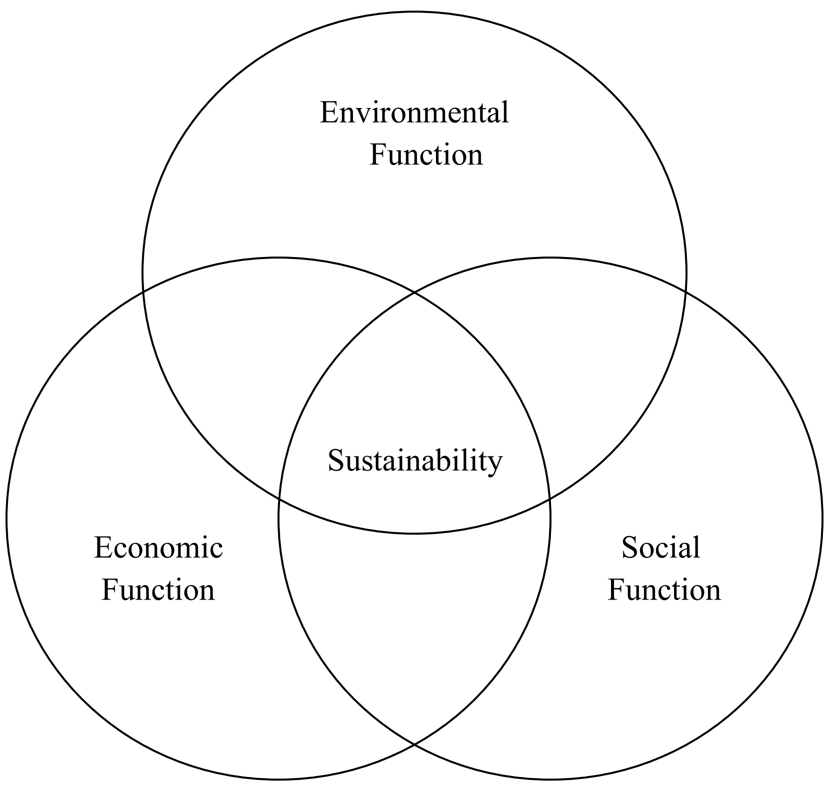

Figure 6 Three Functional Elements of Sustainability

Packaging sustainability can be distinguished between different levels of concern. These different levels of concern are the macro levels of society such as prosperity and well-being, the intermediate levels of the packaging system such as efficiency and effectiveness including product waste prevention, and the micro levels of packaging materials such as closed cycle reuse, zero waste and the safety or non-toxicity of packaging components (Lewis 2005).

There are four principles of sustainable packaging identified by SPA, which consist of effective, efficient, cyclic and clean (Lewis et al. 2007). These four principles are explained in Table 1.

Table 1 Principles of sustainable packaging by SPA (Lewis et al. 2007, p. 4)

Principles of Sustainable Packaging	Indicators
Effective: The packaging system contributes to society by effectively containing and protecting products in supply chains and by supporting informed and responsible consumption.	Reduces product waste
	Improves functionality
	Prevents over-packaging
	Reduces business costs
	Achieves satisfactory return on investment
Efficient: The packaging system is planned to use materials and energy efficiently throughout the product life cycle, interacting with associated support systems such as storage, transport and handling.	Improves product / packaging ratio
	Improves efficiency of logistics
	Improves energy efficiency
	Improves materials efficiency
	Improves water efficiency
	Increases recycled content
	Reduces waste to landfill
Cyclic: Packaging materials used in the system are constantly cycled through the natural or industrial system, minimizing material degradation.	Returnable
	Reusable
	Recyclable
	Biodegradable
Clean: Packaging components used in the system, such as materials, pigments and other additives, do not contain any risks to humans or ecosystems.	Reduces airborne emissions
	Reduces waterborne emissions
	Reduces greenhouse gas emissions
	Reduces toxicity
	Reduces litter impacts

The SPC defined the functions of sustainable packaging (SPC 2009) as follows:

“ • beneficial, safe & healthy for individuals and communities throughout its life cycle;

• meets market criteria for performance and cost;

• sourced, manufactured, transported, and recycled using renewable energy;

• optimizes the use of renewable or recycled source materials;

• manufactured using clean production technologies and best practices;

• made from materials healthy in all probable end-of-life scenarios;

• physically designed to optimize materials and energy;

• effectively recovered and utilized in biological and/or industrial closed loop cycles.”

2.1.3 Increasing business markets for sustainable packaging

The integration of economic, social and environmental performance to achieve sustainable packaging is recognized as a major business challenge for the 21st century (Verghese 2007). Pressure from individuals, governments and social organizations has led to an expectation that manufacturers and retailers need to reduce their packaging. There is also pressure from consumers who are increasingly demanding products with reduced packaging (Unilever 2009). Following this trend, many companies have chosen to use claims of sustainable packaging to stand out in a competitive retail environment.

Sustainability efforts have been used to cut costs and reduce packaging waste for several years. The sustainable packaging industry grew between 2008 and 2009, which differs from other sectors of the packaging industries, and it is expected that the global market of the industry will reach $142.42 billion by 2015 (GIA 2010).

According to a recent report from Pike Research, global packaging industry revenues are expected to increase to $530 billion by 2014, with the sustainable packaging sector comprising $170 billion of that total revenue (Pike Research 2010).

2.1.4 Measurement and design tools for packaging sustainability

There are various methods and tools to consider elements of packaging sustainability and to evaluate their performance, such as the Wal-Mart Packaging Scorecard, PIQUET, and the Olsmats & Dominic Scorecard, as shown in Table 2. Each methodology has its own characteristic and focus, and none covers all environmental impacts of packaging. Therefore, the user of a certain methodology might need further research if important issues or purposes are not covered in the method (Svanes et al. 2010).

Most of the scorecards consider environmental resource indicators. Along with GHG, the Wal-Mart Scorecard emphasizes cube utilization and transport efficiency, which is no surprise since improvements on this score reduce transport cost. The Olsmats & Dominic Scorecard adds measure of resources. PIQUET emphasizes global warming potential and the use of water, land and other resources. Table 2 shows that it is not simple to evaluate sustainability to cover all concerns. Especially, the social aspect of sustainability is hard to quantitatively measure.

Table 2 Sample of tools for sustainable packaging (Svanes et al. 2010, p. 173)

Methodology Characterization	Wal-Mart Packaging Scorecard	Olsmats & Dominic scorecard model (2002)	PIQET
Environmental and resource indicators	GHG emissions Ratio of product / package Cube utilization Transportation efficiency Recycled content Recovery value Use of renewable energy	Volume and weight efficiency Reduced use of resources Minimal use of hazardous substance Minimal amount of waste and packaging	Global warming / climate change Cumulative energy demand Photochemical oxidation Water use Solid waste Land use.
Economy	N.m.	Costs	N.m.
Social elements	N.m.	N.m.	N.m.
Combined system packaging and product	N.m.	N.m.	N.m.
Whole life cycle considered	N.m.	N.m.	N.m.
Product loss considered	No	No	Uncertain
Product protection	N.m.	Considered	Product protection and shelf-life
User Friendliness	N.m.	N.m.	N.m.
Market acceptance	N.m.	Right amount and size Product information Selling capability	Consumer knowledge/ labeling.

N.m. = Not mentioned in description of the methodology.

A complete measure of packaging sustainability would need to consider the environment, economy and social elements, as well as considering the whole life cycle of the product and packaging system including product loss, protection, user friendliness, market acceptance, and disposability. In this way reasonable decisions about sustainability may be made when experts from different areas evaluate together a sustainability issue.

2.2 Life cycle assessment

Life cycle assessment, LCA, is defined by ISO 14040 as "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" including the continuous and successive stages of an entire product system (ISO 1997, pg. 2). Therefore, the LCA is a method for organized assessment of flows connected with all life cycle stages of a product, technology and system (CPA 2010).

An LCA study investigates the potential environmental burdens generated from a product's entire life cycle, including material acquisition, production, physical distribution, and recycling or waste disposal (Manuilova 2003). ISO 14040 guides general principles of LCA (ISO 1997). ISO 14041 guides the development of a life cycle inventory of LCA (ISO 1998), ISO 14042 shows how to evaluate the life cycle impact assessment of LCA (ISO 2000a) and ISO 14043 (ISO 2000b) and 14044 guide interpretation of LCA (ISO 2006).

However, the scope of an LCA does not always have to cover the full scale of life cycle stages since LCA practitioners sometimes need to focus their own scope. Actually, it is common to limit the scope of an LCA to target specific life cycle stages, such as conversion, end of life, or specific environmental indexes, such as energy or resource consumption and global warming (Woolridge et al. 2006).

2.2.1 History of life cycle assessment (LCA)

LCA has its historical roots in pathology, which investigates the life cycle of the pathogen stream at every stage, including monitoring strategies to control it (Mcleod 1999).

In the 1960s, scientists started to use the concept of LCA as an approach to measure the impact of energy consumption since concern was raised about the depletion of fossil fuels. In 1969, the Mid west Research Institute initiated a study of the Coca-Cola Company to investigate which kind of bottle had the lower impact to the environment and required fewer raw materials and energy (Svoboda 1995b). This study might be the first LCA to analyze packaging.

After the Coca-Cola study, the concept of product-related LCA including an emphasis on energy, resources, and waste developed in the early 1970s (Klopffer 2003). Some researchers tried to use computer modeling to forecast the result of interactions between the environment and human systems (Morris 1972). The U.S Environmental Protection Agency (EPA) clarified the methodology formulating Resource and Environmental Profile Analysis (REPA) and conducted approximately fifteen REPAs between 1970 and 1975, prompted by the oil crisis of 1973 (Svoboda 1995b). However, from 1975 to 1988, LCA was not a primary concern of the public since government activity and public attention related to environmental activity was more focused on toxic waste issues such as hazardous waste (Hunt et al. 1996). In 1988, there was an increase of environmental consciousness in the United States, due to national debates and media attention (Hunt et al. 1996).

In May 1990, an international forum by The Conservation Foundation in Washington, D.C. raised awareness to REPA in the United States, followed by the first workshop by the Society of Environmental Toxicology and Chemistry (SETAC) held in August 1990 (Hunt et al. 1996). The terminology, Life Cycle Assessment or Analysis (LCA), was officially adopted to designate the REPA at that time. Two years later, Franklin Associates published an article about the first complete presentation of LCA methodology in a journal in the United States (Hunt et al. 1996). However, LCA was the widely accepted term for only environmental assessments of products on a cradle-to-grave basis (Heijungs et al. 1995). The cradle means the creation and the grave means the final disposal back into the environment (Koneczny et al. 2008).

In the mid 1990s, SETAC Europe, the International Organization for Standardization (ISO), and LCA practitioners worldwide began to develop a specific framework and methodologies (Roy et al. 2009). As a result, LCA was standardized and established officially by the ISO 14040 (ISO 1997).

At the same time, environmental groups around the world began to adopt life cycle analysis. Organizations such as Blue Angel, Green Cross, and Green Seal used and continued to improve LCA for the purpose of product labeling and evaluation (Svoboda 1995b). While initially limited to the public sector, LCA has been adopted by increasing numbers of corporations and nonprofit organizations as an aid to understanding the environmental impacts of their actions. And as demand for “green” products and pressures for environmental quality continued to mount, industrial life cycle analysis became in the 1990s what risk assessment was in the 1980s (Svoboda 1995b).

Today, LCA is increasingly being used to create design of products and systems as well as public policy, to assist decisions in relation to environmentally sustainability (CPA 2010).

2.2.2 Framework of LCA

Within the framework of the ISO standard, an LCA has four phases: scope, life cycle inventory analysis (LCI), life cycle impact analysis, and interpretation of the results (ISO 1997). Figure 7 shows the phases of LCA. Following the phases in the framework, an LCA study is generally performed by developing an inventory of relevant data, evaluating the potential impacts of the inventory, and interpreting the results in relation to the purpose of the study (Finnveden 1999).

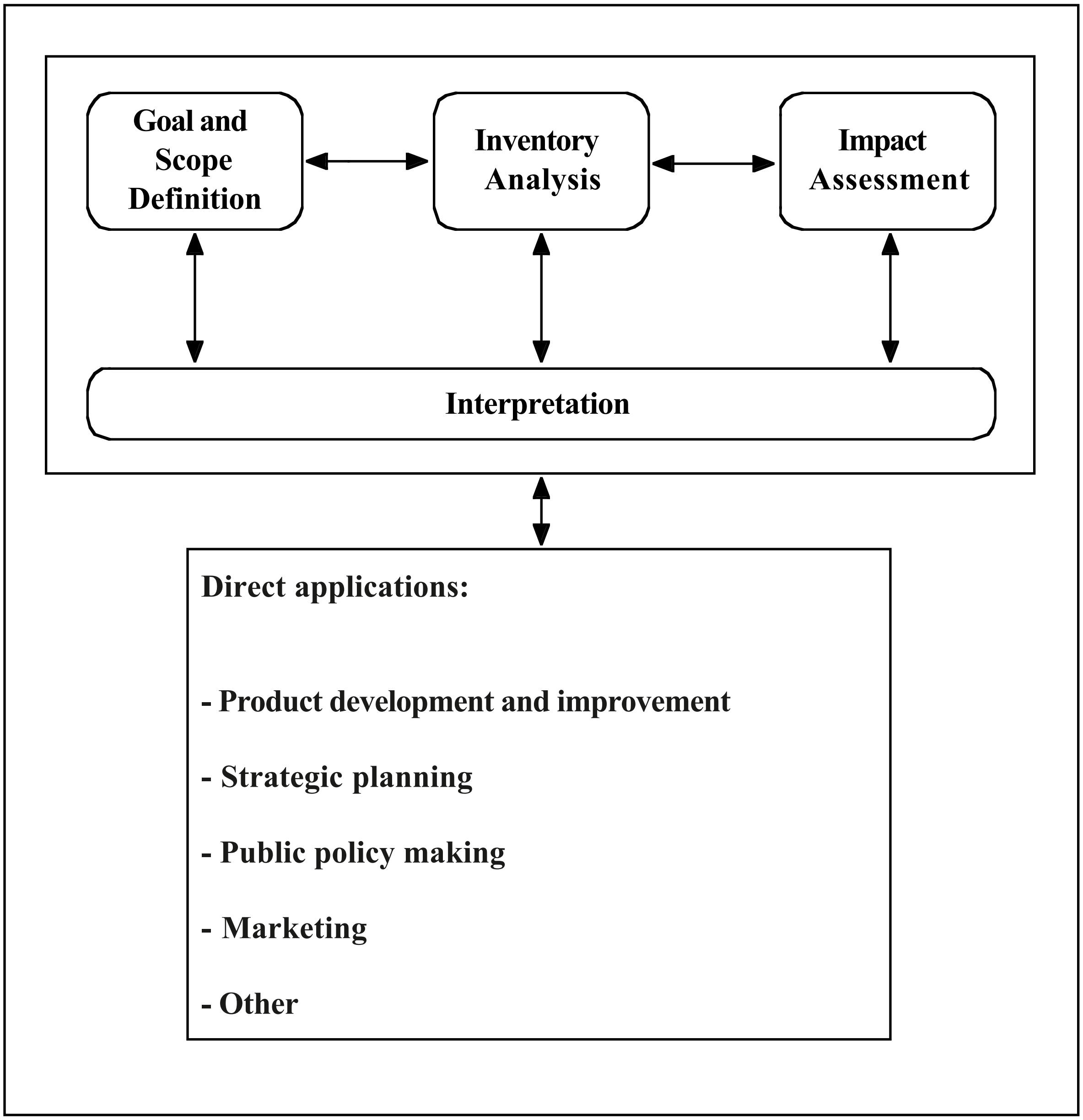

Figure 7 Phases of LCA (ISO 1997)

2.2.2.1 Goal definition and scope

The first step includes clarifying the goal and scope of the LCA. This step is the fundamental element of an LCA. The statements established in this step define the objective, the expected product, system boundaries, functional unit, and assumptions (Roy et al. 2009).

The system boundary is the interface between the environment, other product systems and the product of interest (Woolridge et al. 2006). Table 3 shows examples of system boundaries for LCA.

Table 3 Sample of System Boundaries (Woolridge et al. 2006)

Within system boundary	Outside system boundary
Extraction of resources Manufacture of materials including fuel consumed Electricity generation Packaging processing Packaging distribution Disposal of wastes	Capital equipment All post resale life cycle stages Maintenance of buildings or equipment

The functional unit is the critical basis that enables alternative products or services to be compared and analyzed (Rebitzera 2004). This is required to certify comparability of LCA results, which is especially significant when different systems are assessed, to confirm that such comparisons are performed on a universal basis (ISO 1997). Even though nutritional and economic values of products and land area may also be used, the weight of the product or package under study is generally the basis of the functional unit (Cederberg 2000).

2.2.2.2 Life cycle inventory analysis

The life cycle inventory (LCI) is a list of input flows such as materials and energy used and output flows such as emissions of products to the environment and wastes to be treated. It qualitatively and quantitatively documents them for the product system (CPA 2010).

An LCI is composed of three major elements: planning a process flowchart, collecting data, and calculating the amounts of each data related to the functional unit (Ruggles et al. 2010). The process flowchart involves raw materials, manufacturing processes, transportation, uses, and waste management. The required data are material inputs, products and byproducts, solid waste, air and water emissions, as shown in Figure 8 (Ruggles et al. 2010).

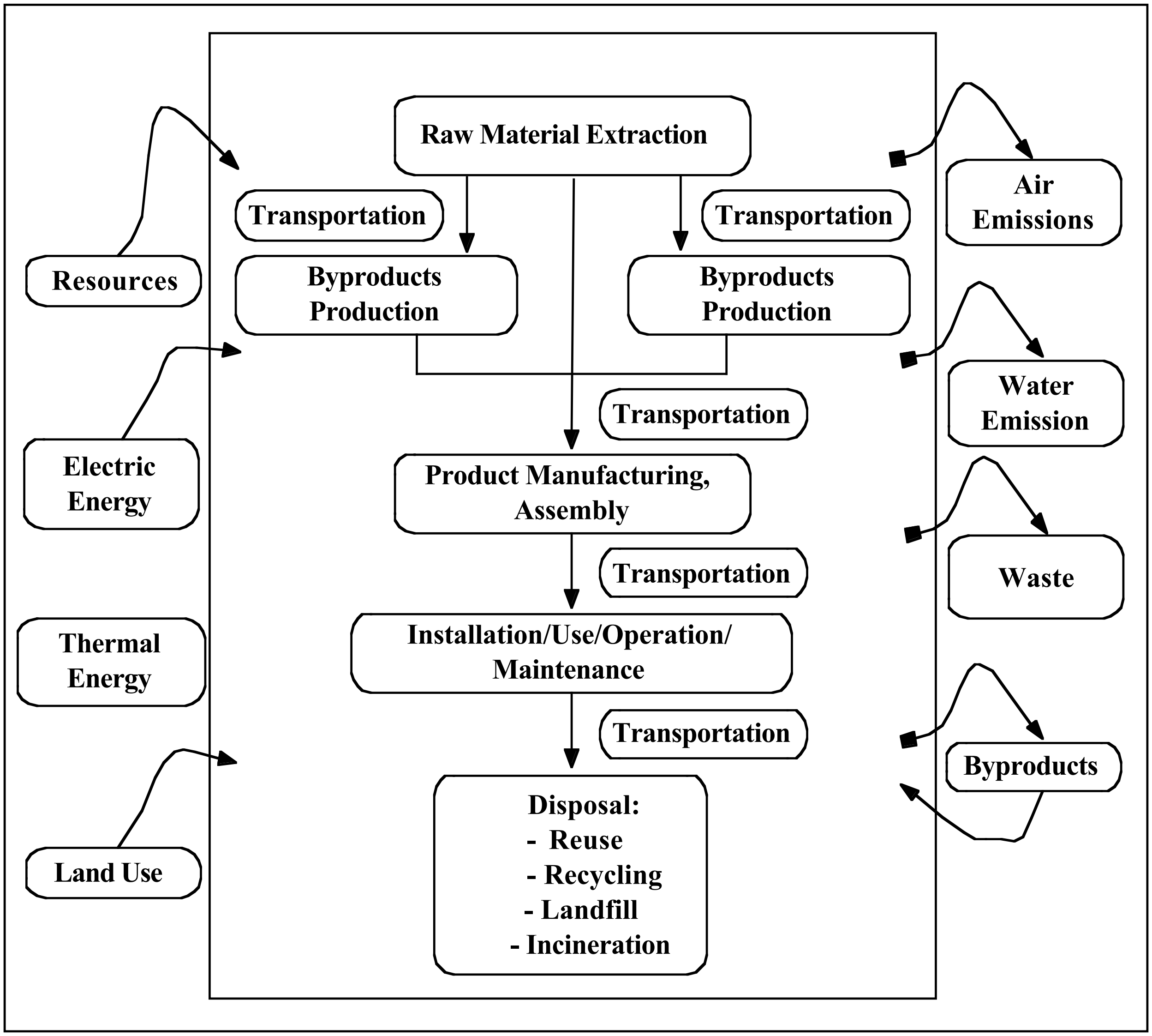

Figure 8 Sample flow chart and required data in the LCI phase (Battisti et al. 2005)

In the life cycle inventory step, the specific data of inputs and outputs for a LCA study are collected throughout all stages of a product's life cycle and calculated for the functional unit (Battisti et al. 2005). Table 4 shows examples of inputs and outputs for the life cycle inventory (LCI).

Table 4 Sample inputs and outputs of LCI

Inputs	Outputs		
	Air Emission	**Water Effluents**	**Solid Waste**
Coal	Carbon dioxide	Chlorides	Industrial Waste
Oil	Hydrocarbons	Phosphates	Municipal Waste
Natural Gas	Methane	Suspended Matter	
Water	Particulates		
Energy			

2.2.2.3 Life cycle impact analysis

A life cycle impact assessment (LCIA) is performed to evaluate environmental impacts, analyzing the data from the inventory analysis. LCIA is a tool to broaden the information and context of LCI data, which is largely mass and energy, and to help determine to what extent a particular environmental factor may be connected with a particular impact category (Saouter et al. 2002). The impact assessment indicates what factors are most important. It becomes a meaningful baseline for improvement (CPA 2010).

Generally, an LCIA consists of four components: classification, characterization, normalization (optional), and valuation (optional). Classification is the process of assigning LCI data into common impact groups. Characterization is the assessment of the magnitude of potential impacts of each inventory flow on its corresponding environmental impact. Normalization is the potential impact, expressed in ways that can be compared. Valuation is the assessment of the relative importance of environmental burdens identified in the classification, characterization, and normalization stages by assigning them weights which allows them to be compared or aggregated (Roy et al. 2009).

The process of selecting or modeling the impact categories is primarily related to the specific concerns of the practitioner (Corti et al. 2007). The inventory results are assigned to different impact categories. Next, contributors to the selected impact assessment categories are identified at a life cycle impact assessment stage. These include global warming, fossil fuel consumption, water consumption, biotic resource consumption, mineral resource consumption, acidification, eutrophication, human toxicity, etc. (Saouter et al. 2002), depending on the requirements of the investigation.

2.2.2.4 Interpretation of LCA

The degree of completeness and consistency of life cycle assessment is evaluated in the interpretation phase (Corti et al. 2007). If one option indicates higher consumption of each material and of each resource when two options are compared, an interpretation absolutely based on the LCI can be conclusive (Rebitzera 2004). However, practitioners may compare values across impact categories, especially if prioritizing within a single life cycle study is required (Rebitzera 2004).

Interpretation occurs at every stage in an LCA, including the ongoing process of clarifying, checking, and evaluating the information from the results of the life cycle inventory and impact assessment phases (Ruggles et al. 2010). Interpretation also communicates the results of the life cycle inventory and impact assessment as the last phase of the LCA process (EPA 2006).

According to ISO 14044, the interpretation phase needs to have several checking points such as checking for completeness, sensitivity, and consistency (ISO 2006). The completeness check is required to confirm that all information and data are available and complete. The sensitivity check is needed to assess the reliability of the final results and conclusions. The consistency check is to determine whether the assumptions, methods, and data are consistent with the goal and scope. Those evaluations are required for reducing uncertainty and unreliability (EPA 2006).

However, there is no solid answer about specific procedures of interpretation in ISO 14044 (Ruggles et al. 2010). The interpretation phase needs more transparent numerical methods for judgment about different cases and purposes. An LCA has many kinds of uncertainty, which may add complexity and unclear results to the interpretation. Therefore, it is significant to discuss and reduce all types of uncertainty in decision-making on the basis of LCA.

There are two basic ways to deal with uncertainties. Procedural approaches rely on discussion of data and results in relation to other sources of information, such as consensus, expert judgment and reputation of the data supplier. Numerical approaches analyze data and results without reference to other sources of information, such as contribution analysis, sensitivity analysis, and uncertainty analysis. The numerical approaches incorporate uncertainties by clearly addressing the consequences of uncertain data for the result, while the procedural approaches focus on reducing uncertainty (Heijungs et al. 2001).

There are five approaches to interpret the data that is produced by an LCA: contribution analysis, perturbation analysis, uncertainty analysis, comparative analysis, and discernibility analysis (Heijungs et al. 2001).

Contribution analysis measures the contribution of the life cycle stages or groups of processes, compared to the total result, and identifies the data that has the greatest contribution to the impact indicator results (EPA 2006).

Perturbation analysis is a form of sensitivity analysis. It refers to slightly changing a coefficient of the model, then observing the changes in the results. Unlike contribution analysis, it covers both economic and environmental flows (Heijungs et al. 2008).

Uncertainty analysis is based on parameter variations and Monte Carlo simulations which are implemented in many LCA software programs. These need information on the uncertainty, such as ranges, distributions, and standard deviations (Heijungs et al. 2008). Simulation, especially Monte Carlo simulation, is very time-consuming because as many as 1,000 runs are generally required to yield reliable results (Morgan et al. 1990). For example, if an LCA calculation of one large system needs 10 seconds, 10,000 Monte Carlo runs consume 100,000 seconds (Heijungs et al. 2001). Moreover, it requires quantitative uncertainty information. In many cases, this is not available, therefore one must make crude assumptions on the data uncertainty.

A comparative analysis is not related to uncertainty, but is only a simultaneous analysis of the product alternatives (Heijungs et al. 2008). Comparative analysis is useful, but it also has some limitations. It is simple but may easily induce claims without a proper analysis of robustness of these claims with respect to the influence of uncertainties.

Discernibility analysis has combined characteristics from both comparative analysis and uncertainty analysis (Heijungs et al. 2008). This method focuses on the number of Monte Carlo runs, as it indicates if a product option is significantly better than another product option (Heijungs et al. 2001). Discernibility analysis may be most closely connected to decision-making procedures.

Table 5 shows how various approaches can be organized, depending on the number of products assessed and whether uncertainty is considered.

Table 5 Overview of five numerical approaches towards life cycle interpretation (Heijungs et al. 2001)

	One product alternative	Several product alternatives
Without uncertainty data	Contribution analysis Perturbation analysis	Comparative analysis
With uncertainty data	Uncertainty analysis Key issue analysis	Discernibility analysis

LCA is a holistic analysis to evaluate the environmental impacts throughout the entire life cycle of a product, process, or activity. Therefore, it may include both quantitative and qualitative measures of improvement, such as changes in product design, raw material usage, industrial processes, consumer use, and waste management (Svoboda 1995b).

2.2.3 LCA application in packaging

Packaging was the industry for which a full LCA study was first applied. In 1969, Harry E. Teasley, Jr. performed the first formal analytical LCA for the Coca-Cola Company, quantifying material and energy consumption and evaluating the environmental burden of its packaging (Hunt et al. 1996). Thereafter, LCA has been continuously applied to various circumstances in relation to packaging industries such as manufacturers, policymakers and waste management companies (Martino 2003).

Manufacturers generally use LCA when they develop or design packaging, as a tool to measure its environmental burden. They use it to compare alternatives before they commence production of the packages. Many companies have proven that LCA can be an efficient tool to check and reduce environmental impacts when it is used for packaging development and improvement (Levy 2000). LCA is able to support business managers when they want to set up their business strategy or marketing plan based on environmental concepts.

However, LCA only indicates the environmental implications of different options and the trade offs that need to be made, instead of giving a clear answer whether the selected option is the winner or loser in the market from the business point of view (Europen 1999). LCA does not evaluate the quality or cost performance of packaging. Therefore, the results developed in an LCA study need to be limited as an element of an integrated decision process, balancing quality and cost performance (Martino 2003).

LCA has been applied in policy making. Governments around the world have utilized the LCA method to evaluate their policies with respect to waste management and packaging. They have developed and promoted its methodological performance by sponsoring research programs and workshops, developing supporting tools, and databases (Rebitzera 2004). They have also used it to help decide the optimal treatment system for packaging waste at an administrative level.

In the United States, several governmental bodies, such as the Environmental Protection Agency (EPA), the Department of Energy (DOE), and the Department of Defense (DOD), are taking part in assisting methodological LCA development, upgrading data availability, and managing research projects (Rebitzera 2004). The LCA tool used by these governmental agencies is the Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) (Bare et al. 2003).

In Japan, beginning in the 1990s, a joint committee composed of LCA experts has organized and conducted LCA activities sponsored by the Ministry of the Environment, Ministry of Agriculture, Forestry and Fisheries, Ministry of Land, Infrastructure and Transport, Ministry of Economy, Trade and Industry, and Ministry of Education, Culture, Sports, Science and Technology (Rebitzera 2004).

In the European Union, LCA is used to provide a badge of acceptance, called an Eco-Label, to packaging that is made using sound environmentally-conscious systems, to enable consumers to make better purchase decisions (Martino 2003). LCA provides the criteria for deciding whether a packaging or product can receive the label (RSC 2005). Policymakers have used it to create regulations for restricting environmentally harmful packaging and to check for fulfillment of the regulations as an objective measure.

However, decisions need to be made on a case-by-case basis, since considerable gaps are detected when LCA is used for policy making at regional levels regarding waste systems (Martino 2003). Corporations and trade organizations argue that the optimal waste management system in one area may not also be the recommended one for other areas, since the extent of diversity between countries, or between regions within the same country, is large (Europen 1999).

2.2.4 LCA software tool COMPASS®

A full LCA requires a lengthy procedure, if it is to be used officially. However, once the inventory is developed, the actual calculation process is fast. As a result, many kinds of LCA software have been developed with built-in inventory data, such as SimaPro, Gabi, Umberto, and COMPASS (Klopffer 2003).

The Sustainable Packaging Coalition (SPC) has developed the Comparative Packaging Assessment, COMPASS, an on-line LCA tool, as a project of the nonprofit institute GreenBlue. It allows packaging designers to model the impacts of their choices while still in the design phase, drawing upon life cycle impact data from the U.S. Life Cycle Inventory (LCI) Database, the European LCI Database and the Canadian LCI Database. It can quantify the life cycle impacts of packaging in various categories such as consumption metrics, emission metrics and packaging attributes. The consumption metrics include fossil fuel, water, biotic resources, and mineral resources. The emission metrics involve greenhouse gases, human impacts, aquatic toxicity, and eutrophication. The packaging attributes category covers material content (virgin or recycled), sourcing, solid waste, and material health (Ruggles et al. 2010).

CHAPTER 3: MATERIALS AND METHODS

In order to evaluate changes in packaging sustainability over time, forty-six packages were investigated in this study. Half of the sample is from a collection of "old" packages that were donated to MSU by Ms. Susan Wineberg of Ann Arbor, Michigan. She has collected diverse consumer packages, such as cartons, glass jars, metal cans, and plastic containers, produced from the 1970s to the 2000s. The other half of the sample was current packages that correspond to the old packages. In March 2011, the current packages were purchased to compare to the old packages.

In order to compare current packages to the old packages, the basis for comparison needs to be accurate and reasonable. Therefore, the criteria for purchasing the current packages were to acquire the same brand names, net weights, packaging materials and company names, compared to the old packages. However, some packages have changed their packaging materials and net weights, and some brands are now sold by different companies. In cases where the current packages did not match the old packages, the packages that were most similar were purchased.

3.1 Dating the packages

Labels and code dates from the old packages were used to investigate the age of the old packages.

However, some of the old packages have no imprinted information about their production or "use by" years. In these cases, the information was found in magazines, comparing the old samples to descriptions in the articles and advertisements.

If there were no information about their production years, Internet webpages of the companies and personal contacts with the companies were used to determine the years.

Some of these kinds of packages are listed as having only approximate production years, such as ‘before 1991’ and ‘1986-1990’. The uncertain manufacturing years are not critical problems in this study, since they do not affect the purpose of this study, which is comparing old packages to the current ones.

Among the twenty-three old packages, three packages were produced in the 1970s, ten packages were produced in the 1980s, four packages were produced in the 1990s, three packages were produced in the 2000s, and three could only be identified as produced before 1991.

Most of the current packages were produced in 2011, except one package that was produced in 2007. The reason why this package was selected is explained in the description of Sample Group 9 in Chapter 3.3.2.

3.2 Goal and scope

The goal of the LCA in this study is to investigate the environmental sustainability performance of diverse packages, which were produced from the 1970s to 2011, in order to evaluate trends in packaging sustainability.

The LCA model of this study was created using the COMPASS software system for life cycle assessment developed by SPC. The data bases contained in the COMPASS provide the LCI data for raw materials used in the background system (Mistry 2010b).

In COMPASS, there are four stages of a package’s life cycle: manufacturing, conversion, distribution, and end of life. The distribution stage was not investigated in this study, since it is difficult to get information about the specific supply chains of the past from each manufacturing company, and there are no shipping containers in the study. Therefore, the scope of the LCA in this study includes:

- Production of raw materials, energy consumption and electricity needed for the manufacture of the packages,
- Conversion of materials to a final product involving manufacturing processes,
- End of life including disposal such as landfill and incineration, and recovery such as recycling and waste to energy.

COMPASS affords three levels of packaging analysis: primary packaging, secondary packaging and packaging system. The primary packaging means ‘the customer facing packaging which may be a single material package or multi-material composite and/or multi-component package assembly’. The secondary package is generally ‘used to transport or to store the primary customer facing package’. The packaging system means that ‘combination of some unit count of a primary package inside a secondary package’ (Mistry 2010a).

However, only primary packaging was investigated in this study. The secondary packaging and packaging system were not included in this study, since there was no access to specific data from the past.

The functional unit used in this study was generally 1000 kilograms or 1000 liters of the product. For beverages, which are usually sold by fluid ounces or milliliters, 1000 liters was used as the functional unit. The rest of the products, sold by weight, were analyzed on the basis of 1000 kilograms.

The functional unit of Sample Group 9 is 500 kilograms, different from the others. This is because COMPASS cannot accommodate any data that exceeds 1,000,000. The weight of glass jars in Group 9 is 1,370,000, which exceeds 1,000,000, when the functional unit is set to 1000 kg, so the functional unit size had to be reduced.

3.3 Description of evaluated samples

There were twenty-three sample groups and forty-six packaging samples in this study. The sample groups were divided into four categories based on materials in the old packaging samples: paperboard, glass, metal and rigid plastics. Each category had three to eight sample groups. A fifth category was assigned for hamburger packages from McDonald's, because various kinds of McDonald's packages were donated. Each sample group consisted of an old package sample and a current one for comparison. Some of the old samples had different materials from the current samples, and others had the same materials as the current ones.

3.3.1 Category 1: Paperboard cartons

The product in Sample Group 1 was Kellogg's Corn Flakes cereal, manufactured by the Kellogg Company. The old package was manufactured in 1973, and the current package was produced in 2011. Both are Partial-Overlap Seal End (POSE) cartons, which are made from clay coated recycled board (CRB). The inner packages were not included because the old sample was missing the inner package. Figure 9 shows the old package in Sample Group 1, and Figure 10 shows the current package in Sample Group 1.

Figure 9 Old package sample in Sample Group 1. For interpretation of the references to color in this and all other figures, the reader is referred to the electronic version of this thesis.

Figure 10 Current package sample in Sample Group 1

Table 6 shows specific descriptions of Sample Group 1. The weights of packaging components are inputs to COMPASS based on the functional units.

Table 6 Description of Sample Group 1.

Sample Number	1.1	1.2
Name of Product	Kellogg's Corn Flakes Cereal	Kellogg's Corn Flakes Cereal
Name of Company	Kellogg Company	Kellogg Company
Manufacturing Year	1973	2011
Net Contents	24 OZ	24 OZ
Functional Unit	1000 kg	1000 kg
Description & Data inputs based on the functional units	Partial-Overlap Seal End (POSE) Carton: Clay Coated Recycled Board (CRB): 202500.0 g	POSE Carton: CRB: 203970.6 g

The product in Sample Group 2 was Ritz-Crackers, manufactured by the Nabisco Company. The old package was manufactured in 1983, and the current package was produced in 2011. Both are POSE cartons, which were made from clay coated recycled board. The inner packages are not included because the old one was missing the inner package. Figure 11 shows the old package in Sample Group 2, and Figure 12 shows the current package in Sample Group 2.

Figure 11 Old package sample in Sample Group 2

Figure 12 Current package sample in Sample Group 2

Table 7 shows specific descriptions of Sample Group 2. The weights of packaging components are inputs to COMPASS based on the functional units.

Table 7 Description of Sample Group 2.

Sample Number	**2.1**	**2.2**
Name of Product	Ritz-Crackers	Ritz-Crackers
Name of Company	Nabisco, Kraft Foods	Nabisco, Kraft Foods
Manufacturing Year	1983	2011
Net Contents	16 OZ	16 OZ
Functional Unit	1000 kg	1000 kg
Description & Data inputs based on the functional units	POSE: CRB: 153964.8 g	POSE: CRB: 145033.1 g

The product in Sample Group 3 was Post Grape-Nuts, manufactured by Post Foods, LLC. The old package was manufactured in 1989, and the current package was produced in 2011. Both are POSE cartons, made from CRB. The inner packages were not included because the old one was missing the inner package. This sample has a weight difference; the net weight of the old one was 1800 g, but that of the current one was 680 g. Figure 13 shows the old package in Sample Group 3, and Figure 14 shows the current package in Sample Group 3.

Figure 13 Old package sample in Sample Group 3

Figure 14 Current package sample in Sample Group 3

Table 8 shows specific descriptions of Sample Group 3. The weights of packaging components are inputs to COMPASS based on the functional units.

Table 8 Description of Sample Group 3.

Sample Number	3.1	3.2
Name of Product	Post Grape-Nuts	Post Grape-Nuts
Name of Company	Post Foods, LLC	Post Foods, LLC
Manufacturing Year	1989	2011
Net Contents	63 OZ	24 OZ
Functional Unit	1000 kg	1000 kg
Description & Data inputs based on the functional units	POSE Carton: CRB: 88000.0 g	POSE Carton: CRB: 67205.9 g

The product in Sample Group 4 was Quaker Oats, manufactured by the Quaker Oats Company. The old package was manufactured in 2001, and the current package was produced in 2011. Both have a spiral-wound tube style carton made from coated recycled board with a white, clay coated top sheet and a cap made from clay coated recycled board with a low-density polyethylene edge. The old one used polyvinyl chloride film induction-sealed for tamper evidence, but the current one has corn-based polylactide (PLA) film. Figure 15 shows the old package in Sample Group 4, and Figure 16 shows the current package in Sample Group 4.

Figure 15 Old package sample in Sample Group 4

Figure 16 Current package sample in Sample Group 4

Table 9 describes Sample Group 4. The weights of packaging components are inputs to COMPASS based on the functional units.

Table 9 Description of Sample Group 4.

Sample Number	**4.1**	**4.2**
Name of Product	Quaker Oats	Quaker Oats
Name of Company	Quaker Oats Company	Quaker Oats Company
Manufacturing Year	2001	2011
Net Contents	18 OZ	18 OZ
Functional Unit	1000 kg	1000 kg
Description & Data inputs based on the functional units	Tube Style Carton: CRB: 93333.3 g	Tube Style Carton: CRB: 75294.1 g
	Cap: LDPE: 13725.5 g + CRB: 4313.7 g	Cap: LDPE 14117.6 g + CRB: 4117.6 g
	Tamper Evidence: PVC: 2745.1 g	Tamper Evidence: Corn Based PLA: 1568.6 g

3.3.2 Category 2: Glass bottles and jars

The product in Sample Group 5 is Coca-Cola, manufactured by the Coca-Cola Company. The old package was manufactured in 1971, and the current package was produced in 2011. Both are glass bottles without caps. The net volume of the old one is 476 ml, while that of the current one is 237 ml. Figure 17 shows the old package in Sample Group 5, and Figure 18 shows the current package in Sample Group 5.

Figure 17 Old package sample in Sample Group 5

Figure 18 Current package sample in Sample Group 5

The specific description of Sample Group 5 is shown in Table 10. The weights of packaging components are inputs to COMPASS based on the functional units.

Table 10 Description of Sample Group 5.

Sample Number	5.1	5.2
Name of Product	Coca-Cola Coke	Coca-Cola Coke
Name of Company	Coca-Cola Company	Coca-Cola Company
Manufacturing Year	1971	2011
Net Contents	16 FL OZ	8 FL OZ
Functional Unit	1000L	1000L
Description & Data inputs based on the functional units	Glass Bottle: 898949.6 g	Glass Bottle: 724050.6 g

The product in Sample Group 6 is Campbell's Minestrone Condensed Soup, manufactured by the Campbell Soup Company. The old package was manufactured in 1997, and the current package was produced in 2011. These two packages have different net weights and materials. The old package is a glass jar, which has an aluminum cap and a paper label, while the current package is a steel can, which has steel ends, a steel ring-pull, and a paper label. Moreover, the net weight of the old package is 680g and that of the current one is 305g. The reason why these packages are totally different from each other is that the company does not produce the product in the glass jar anymore, but does produce it packaged in a steel can. Figure 19 shows the old package in Sample Group 6, and Figure 20 shows the current package in Sample Group 6.

Figure 19 Old package sample in Sample Group 6

Figure 20 Current package sample in Sample Group 6

Table 11 describes Sample Group 6. The weights of packaging components are inputs to COMPASS based on the functional units.

Table 11 Description of Sample Group 6.

Sample Number	6.1	6.2
Name of Product	Campbell's Minestrone Condensed Soup	Campbell's Minestrone Condensed Soup
Name of Company	Campbell Soup Company	Campbell Soup Company
Manufacturing Year	1997	2011
Net Contents	24 OZ	10 ¾ OZ
Functional Unit	1000 kg	1000 kg
Description & Data inputs based on the functional units	Glass Jar: 538823.5 g	Steel Can: 120221.3 g
	Cap: Steel: 26176.5 g	Lid: Steel lid with a steel ring-pull: 20000.0 g
	Label: Bleached Paper: 882.4 g	Label: Bleached Paper: 4918.0 g

The product in Sample Group 7 is Heinz Tomato Ketchup, manufactured by the Heinz Company. The old package was manufactured in 1992, and the current package was produced in 2011. These two packages have the same net weight, but they have different packaging materials, since the company no longer packs ketchup in glass bottles. The old package is a glass bottle, which has a steel cap and a paper label. The current package is a top-down polyethylene terephthalate (PET) bottle with a polypropylene (PP) cap, aluminum foil induction seal, and paper label. According to the website of the Heinz Company, the glass bottle is still made and only sold to restaurants these days (Heinz 2011). The corresponding current package to the old one is not the glass container for restaurants but the PET container for family use. Figure 21 shows the old package in Sample Group 7, and Figure 22 shows the current package in Sample Group 7.

Figure 21 Old package sample in Sample Group 7

Figure 22 Current package sample in Sample Group 7

The specific description of Sample Group 7 is explained in Table 12. The weights of packaging components are inputs to COMPASS based on the functional units.

Table 12 Description of Sample Group 7.

Sample Number	7.1	7.2
Name of Product	Heinz Tomato Ketchup	Heinz Tomato Ketchup
Name of Company	Heinz Company	Heinz Company
Manufacturing Year	1992	2011
Net Contents	14 OZ	14 OZ
Functional Unit	1000 kg	1000 kg
Description & Data inputs based on the functional units	Glass Container: 531989.9 g	Top-down PET bottle: 78085.6 g
	Cap: Steel: 8816.1 g	Cap: Polypropylene (PP): 36272.0 g
	Label: Bleached Paper: 755.7 g	Pull Tab Opening: Aluminum Foil: 503.8 g
		Label: Bleached Paper: 1007.6 g

The product in Sample Group 8 is Heinz Apple Cider Vinegar, manufactured by the Heinz Company. The old package was manufactured in 1995, and the current package was produced in 2011. They are glass bottles with a paper label. However, the old one has a steel cap, while the current one has a PP cap. Figure 23 shows the old package in Sample Group 8, and Figure 24 shows the current package in Sample Group 8.

Figure 23 Old package sample in Sample Group 8

Figure 24 Current package sample in Sample Group 8

Table 13 shows the characteristics of Sample Group 8. The weights of packaging components are inputs to COMPASS based on the functional units.

Table 13 Description of Sample Group 8.

Sample Number	8.1	8.2
Name of Product	Heinz Apple Cider Vinegar	Heinz Apple Cider Vinegar
Name of Company	Heinz Company	Heinz Company
Manufacturing Year	1995	2011
Net Contents	16 FL OZ	16 FL OZ
Functional Unit	1000L	1000L
Description & Data inputs based on the functional units	Glass Container: 533826.6 g	Glass Container: 509302.3 g
	Cap: Aluminum: 3171.2 g	Cap: PP: 5074.0 g
	Label: Bleached Paper: 3382.7 g	Label: Bleached Paper: 2959.8 g

The product in Sample Group 9 is Kraft Grated Romano Cheese, manufactured by Kraft Foods. The old package was manufactured in 1980. This product is not currently sold in any stores, because the company stopped production in 2007. Therefore, a newer package produced in 2007 was purchased via an online website. The old one is a glass jar with an aluminum cap, a paper lid between the cap and the glass, and paper label, while the new one is a PET container with a PP cap, aluminum tab, and PP label. The net weight of the old product is 170g, and that of the new one is 227g. Figure 25 shows the old package in Sample Group 9, and Figure 26 shows the current package in Sample Group 9.

Figure 25 Old package sample in Sample Group 9

Figure 26 Current package sample in Sample Group 9

Sample Group 9 is shown in Table 14. The weights of packaging components are inputs to COMPASS based on the functional units.

Table 14 Description of Sample Group 9.

Sample Number	9.1	9.2
Name of Product	Kraft Romano Cheese	Kraft Romano Cheese
Name of Company	Kraft Foods	Kraft Foods
Manufacturing Year	1980	2007
Net Contents	6 OZ	8 OZ
Functional Unit	500 kg	500 kg
Description & Data inputs based on the functional units	Glass Jar: 684117.6 g	PET Container: 61894.3 g
	Cap: Steel: 25588.2 g	Cap: PP: 29074.9 g
	Lid: Liquid Packaging Board (LPB): 5588.2 g	Pull Tab Opening: Aluminum: 1321.6 g
	Label: Bleached Paper: 882.4 g	Label: PP: 1982.4 g

The product in Sample Group 10 is Tropicana Orange Juice, manufactured by the Tropicana Company. The old package was manufactured in 1975, and the current package was produced in 2011. The old package is a glass jar with a steel cap. The current one is a composite gable-top paperboard carton, which is made of solid bleached sulfate (SBS) paperboard coated with low-density polyethylene (LDPE). It has a PP cap, a pour spout made of low-density polyethylene (LDPE), and a pull opening tab made of LDPE. Figure 27 shows the old package in Sample Group 10, and Figure 28 shows the current package in Sample Group 10.

Figure 27 Old package sample in Sample Group 10

Figure 28 Current package sample in Sample Group 10

Table 15 shows the properties of packages in Sample Group 10. The weights of packaging components are inputs to COMPASS based on the functional units.

Table 15 Description of Sample Group 10.

Sample Number	10.1	10.2
Name of Product	Tropicana Orange Juice	Tropicana Orange Juice
Name of Company	Tropicana Company	Tropicana
Manufacturing Year	1975	2011
Net Contents	32 FL OZ	59 FL OZ
Functional Unit	1000L	1000L
Description & Data inputs based on the functional units	Glass Jar: 454334.0 g	Solid Bleached Sulfate (SBS) Paperboard: 36349.8 g + LDPE gable-top carton: 1135.9 g
	Cap: PP: 8773.8 g	Cap: PP: 914.3 g
		Pour Spout: Low-Density Polyethylene (LDPE): 685.7 g
		Tab: LDPE: 342.9 g

3.3.3 Category 3: Metal cans

The product in Sample Group 11 is Coca-Cola, manufactured by the Coca-Cola Company. The old package was manufactured in 1984, and the current package was produced in 2011. Both packages are two-piece aluminum cans. Figure 29 shows the old package in Sample Group 11, and Figure 30 shows the current package in Sample Group 11.

Figure 29 Old package sample in Sample Group 11

Figure 30 Current package sample in Sample Group 11

Table 16 describes the packages in Sample Group 11. The weights of packaging components are inputs to COMPASS based on the functional units.

Table 16 Description of Sample Group 11.

Sample Number	**11.1**	**11.2**
Name of Product	Coca-Cola Coke	Coca-Cola Coke
Name of Company	Coca-Cola Company	Coca-Cola Company
Manufacturing Year	1984	2011
Net Contents	12 OZ	12 OZ
Functional Unit	1000L	1000L
Description & Data inputs based on the functional units	Two-Piece Aluminum Can: 52542.4 g	Two-Piece Aluminum Can: 39154.9 g

The product in Sample Group 12 is Diet Coke, manufactured by the Coca-Cola Company. The old package was manufactured in 1980, and the current package was produced in 2011. Both packages are two-piece aluminum cans. Figure 31 shows the old package in Sample Group 12, and Figure 32 shows the current package in Sample Group 12.

Figure 31 Old package sample in Sample Group 12

Figure 32 Current package sample in Sample Group 12

Sample Group 12 is described in Table 17. The weights of packaging components are inputs to COMPASS based on the functional units.

Table 17 Description of Sample Group 12.

Sample Number	12.1	12.2
Name of Product	Coca-Cola Diet Coke	Coca-Cola Diet Coke
Name of Company	Coca-Cola Company	Coca-Cola Company
Manufacturing Year	1980	2011
Net Weight	12 FL OZ	12 FL OZ
Functional Unit	1000L	1000L
Description	Two-Piece Aluminum Can: 53107.3 g	Two-Piece Aluminum Can: 37464.8 g

The product in Sample Group 13 is Maxwell House Coffee, manufactured by Kraft Foods. The old package was manufactured in 1987, and the current package was produced in 2011. The old package is a large steel can with a low-density polyethylene (LDPE) snap cap. The company still sells coffee in the steel can package, but only uses the can for small capacity products, while a high-density polyethylene (HDPE) container is used for large capacity products. Therefore, the high-density polyethylene container with a polypropylene lid and an aluminum seal cover is selected as the current package in this study. Figure 33 shows the old package in Sample Group 13, and Figure 34 shows the current package in Sample Group 13.

Figure 33 Old package sample in Sample Group 13

Figure 34 Current package sample in Sample Group 13

Table 18 describes the packages in Sample Group 13. The weights of packaging components are inputs to COMPASS based on the functional units.

Table 18 Description of Sample Group 13.

Sample Number	13.1	13.2
Name of Product	Maxwell House Coffee	Maxwell House Coffee
Name of Company	Kraft Foods	Kraft Foods
Manufacturing Year	1987	2011
Net Contents	32 OZ	34.5 OZ
Functional Unit	1000 kg	1000 kg
Description & Data inputs based on the functional units	Steel Can: 189305.4 g	HDPE Jar: 142842.5 g
	Lid: LDPE: 14994.5 g	Lid: PP: 22903.9 g
		Induction Seal Cover: Aluminum: 2965.2 g

3.3.4 Category 4: Rigid plastic

The product in Sample Group 14 is Coca-Cola, manufactured by the Coca-Cola Company. The old package was manufactured in 1986, and the current package was produced in 2011. The old package is a PET bottle with an aluminum cap and a PP label. It also has a PP cup, which covers the bottom of the bottle. The current one is a PET bottle with a PP cap and label.

Figure 35 shows the old package in Sample Group 14, and Figure 36 shows the current package in Sample Group 14.

Figure 35 Old package sample in Sample Group 14

Figure 36 Current package sample in Sample Group 14

Table 19 describes Sample Group 14. The weights of packaging components are inputs to COMPASS based on the functional units.

Table 19 Description of Sample Group 14.

Sample Number	14.1	14.2
Name of Product	Coca-Cola Coke	Coca-Cola Coke
Name of Company	Coca-Cola Company	Coca-Cola Company
Manufacturing Year	1986	2011
Net Contents	16 FL OZ	16 FL OZ
Functional Unit	1000L	1000L
Description & Data inputs based on the functional units	PET: 49471.5 g	PET: 51923.7 g
	Base Cup: PP: 13530.7 g	Cap: PP: 4651.2 g
	Cap: Aluminum: 3382.7 g	Label: PP: 507.6 g
	Label: PP: 634.2 g	

The product in Sample Group 15 is Kraft Grated Parmesan Cheese, manufactured by Kraft Foods. The old package was manufactured in 1986, and the current package was produced in 2011. The net content of the old package is 227 g, while that of the current one is 249 g. Both packages are a PET container with a PP cap, an aluminum seal opening, and PP label. Figure 37 shows the old package in Sample Group 15, and Figure 38 shows the current package in Sample Group 15.

Figure 37 Old package sample in Sample Group 15

Figure 38 Current package sample in Sample Group 15

Table 20 describes Sample Group 15. The weights of packaging components are inputs to COMPASS based on the functional units.

Table 20 Description of Sample Group 15.

Sample Number	15.1	15.2
Name of Product	Kraft Grated Parmesan Cheese	Kraft Grated Parmesan Cheese
Name of Company	Kraft Foods	Kraft Foods
Manufacturing Year	1986	2011
Net Contents	8 OZ	8.8 OZ
Functional Unit	1000 kg	1000 kg
Description & Data inputs based on the functional units	PET Container: 132158.6 g	PET Container: 124096.4 g
	Cap: PP: 65638.8 g	Cap: PP: 58232.9 g
	Pull Tap Opening: Aluminum: 2643.2 g	Pull Tap Opening: Aluminum: 2409.6 g
	Label: PP: 5286.3 g	Label: PP: 4417.7 g

The product in Sample Group 16 is JIF Creamy Peanut Butter, manufactured by General Mills. The old package was manufactured in 1988, and the current package was produced in 2011. Both packages are a PET jar with a polypropylene cap and paper label. However, the induction seal of the old package is made from aluminum foil, while that of the current package is made from aluminum foil laminated to bleached paper. Figure 39 shows the old package in Sample Group 16, and Figure 40 shows the current package in Sample Group 16.

Figure 39 Old package sample in Sample Group 16

Figure 40 Current package sample in Sample Group 16

Table 21 describes packages in Sample Group 16. The weights of packaging components are inputs to COMPASS based on the functional units.

Table 21 Description of Sample Group 16.

Sample Number	16.1	16.2
Name of Product	JIF Creamy Peanut Butter	JIF Creamy Peanut Butter
Name of Company	General Mills	General Mills
Manufacturing Year	1988	2011
Net Contents	18 OZ	18 OZ
Functional Unit	1000 kg	1000 kg
Description & Data inputs based on the functional units	PET Container: 62549.0 g	PET Container: 51372.5 g
	Cap: PP: 29411.8 g	Cap: PP: 19215.7 g
	Induction seal: Aluminum: 784.3 g	Pull Tap Opening: Aluminum: 1372.5 g + Bleached Paper: 1176.5 g
	Label: Bleached Paper: 3137.2 g	Label: Bleached Paper: 2941.2 g

The product in Sample Group 17 is Dannon Fat Free Plain Yogurt, manufactured by the Dannon Company. The old package was manufactured in 1990, and the current package was produced in 2011. They are PP cups with PP caps and have the same net weight. Figure 41 shows the old package in Sample Group 17, and Figure 42 shows the current package in Sample Group 17.

Figure 41 Old package sample in Sample Group 17

Figure 42 Current package sample in Sample Group 17

Table 22 describes packages in Sample Group 17. The weights of packaging components are inputs to COMPASS based on the functional units.

Table 22 Description of Sample Group 17.

Sample Number	17.1	17.2
Name of Product	Dannon Plain Yogurt	Dannon Plain Yogurt
Name of Company	The Dannon Company Inc.	The Dannon Company Inc.
Manufacturing Year	1986-1990	2011
Net Contents	32 OZ	32 OZ
Functional Unit	1000 kg	1000 kg
Description & Data inputs based on the functional units	PP Cup: 41345.1 g	PP Cup: 31312.0 g
	PP Cap: 12899.7 g	PP Cap: 6174.2 g

The product in Sample Group 18 is Dannon Yogurt, manufactured by the Dannon Company. The old package was manufactured in 2000, and the current package was produced in 2011. Both are polypropylene containers with an aluminum foil induction-sealed lid. Figure 43 shows the old package in Sample Group 18, and Figure 44 shows the current package in Sample Group 18.

Figure 43 Old package sample in Sample Group 18

Figure 44 Current package sample in Sample Group 18

Table 23 explains both packages in the sample group 18. The weights of packaging components are inputs to COMPASS based on the functional units.

Table 23 Description of Sample Group 18.

Sample Number	18.1	18.2
Name of Product	Dannon Yogurt	Dannon Yogurt
Name of Company	The Dannon Company Inc.	The Dannon Company Inc.
Manufacturing Year	2000	2011
Net Contents	6 OZ	8 OZ
Functional Unit	1000 kg	1000 kg
Description & Data inputs based on the functional units	PP Container: 57709.3 g	PP Container: 41176.5 g
	Aluminum Foil Lid: 3083.7 g	Aluminum Foil Lid: 3529.4 g

The product in Sample Group 19 is Absopure bottled water, manufactured by the Absopure Water Corporation. The old package was manufactured in 2004, and the current package was produced in 2011. Both packages are a PET bottle with a polypropylene cap and a polypropylene label. Figure 45 shows the old package in Sample Group 19, and Figure 46 shows the current package in Sample Group 19.

Figure 45 Old package sample in Sample Group 19

Figure 46 Current package sample in Sample Group 19

Table 24 describes the packages in Sample Group 19. The weights of packaging components are inputs to COMPASS based on the functional units.

Table 24 Description of Sample Group 19.

Sample Number	**19.1**	**19.2**
Name of Product	Absopure Water	Absopure Water
Name of Company	Absopure Water Corporation	Absopure Water Corporation
Manufacturing Year	2004	2011
Net Contents	25 FL OZ	25 FL OZ
Functional Unit	1000L	1000L
Description & Data inputs based on the functional units	PET Bottle: 31258.5 g	PET Bottle: 30717.2 g
	Cap: PP: 6224.6 g	Cap: PP: 4465.5 g
	Label: PP: 676.6 g	Label: PP: 676.6 g

The product in Sample Group 20 is Hershey's Syrup Chocolate, manufactured by the Hershey Company. The old package was manufactured in 1999, and the current package was produced in 2011. Both packages are a high-density polyethylene container having a PP cap. However, the old package has a cap cover made of PP and a paper label. The new package is directly printed. Figure 47 shows the old package in Sample Group 20, and Figure 48 shows the current package in Sample Group 20.

Figure 47 Old package sample in Sample Group 20

Figure 48 Current package sample in Sample Group 20

Table 25 describes packages in Sample Group 20. The weights of packaging components are inputs to COMPASS based on the functional units.

Table 25 Description of Sample Group 20.

Sample Number	20.1	20.2
Name of Product	Hershey's Syrup Chocolate	Hershey's Syrup Chocolate
Name of Company	The Hershey Company	The Hershey Company
Manufacturing Year	1999	2011
Net Contents	26 OZ	24 OZ
Functional Unit	1000 kg	1000 kg
Description & Data inputs based on the functional units	HDPE Container: 63365.0 g	HDPE Container: 60000.0 g
	Cap: PP: 7327.0 g	Cap: PP: 7647.1 g
	Cover: PP: 1899.6 g	
	Label: Bleached Paper: 542.7 g	

3.3.5 Category 5: McDonald's

The product in Sample Group 21 is a Big Mac hamburger sandwich, sold by McDonald's Corporation. The old package was manufactured before 1991, and the current package was produced in 2011. The old package did not have a printed manufacturing year. However, the company announced that the package for this product was switched from expanded polystyrene (EPS) clamshell to waxed paper in 1991 (Svoboda 1995a). They switched the package from standard paperboard clamshell to a lightweight paperboard clamshell in 2003. According to the corporate communications department of McDonald's Corporation, "The packaging is very lightweight compared to standard paperboard clamshell packaging, incorporates unbleached fibers, and contains 46 percent postconsumer content" (*Why Did McDonald's Switch?* 2005).

The old package is an EPS clamshell, while the current one is an F-flute corrugated clamshell made from unbleached paper liners and recycled medium. The paperboard clamshell for the current package contains 37 percent post-consumer recycled (PCR) fiber. Figure 49 shows the old package in Sample Group 21, and Figure 50 shows the current package in Sample Group 21.

Figure 49 Old package sample in Sample Group 21

Figure 50 Current package sample in Sample Group 21

Table 26 describes the packages in Sample Group 21.

Table 26 Description of Sample Group 21.

Sample Number	21.1	21.2
Name of Product	Big Mac	Big Mac
Name of Company	McDonald's Corporation	McDonald's Corporation
Manufacturing Year	Before 1991	2011
Net Contents	7.5 OZ	7.5 OZ
Functional Unit	1000 kg	1000 kg
Description	EPS Clamshell: 25233.6 g	F-flute Corrugated Clamshell: Unbleached Liners + Recycled medium, 37% PCR: 53738.3 g

The product in Sample Group 22 is a Quarter Pounder with Cheese hamburger sandwich, sold by McDonald's Corporation. The old package was manufactured before 1991, and the current package was produced in 2011. The materials of both packages are same as those of samples in Group 21. Figure 51 shows the old package in Sample Group 22, and Figure 52 shows the current package in Sample Group 22.

Figure 51 Old package sample in Sample Group 22

Figure 52 Current package sample in Sample Group 22

Table 27 shows the packages in Sample Group 22.

Table 27 Description of Sample Group 22.

Sample Number	22.1	22.2
Name of Product	Quarter Pounder with Cheese	Quarter Pounder with Cheese
Name of Company	McDonald's Corporation	McDonald's Corporation
Manufacturing Year	Before 1991	2011
Net Contents	7 OZ	7 OZ
Functional Unit	1000 kg	1000 kg
Description	EPS Clamshell: 24242.4 g	F-flute Corrugated Clamshell: Unbleached Liner + Recycled Paper, 37% PCR: 57070.7 g

The product in Sample Group 23 is a Filet-O-Fish sandwich, sold by McDonald's Corporation. The old package was manufactured before 1991, and the current package was produced in 2011. The materials of both packages are same as those of samples in Groups 21 and 22. Figure 53 shows the old package in Sample Group 23, and Figure 54 shows the current package in Sample Group 23.

Figure 53 Old package sample in Sample Group 23

Figure 54 Current package sample in Sample Group 23

Table 28 describes the packages in Sample Group 23.

Table 28 Description of Sample Group 23.

Sample Number	23.1	23.2
Name of Product	Filet-O-Fish	Filet-O-Fish
Name of Company	McDonald's Corporation	McDonald's Corporation
Manufacturing Year	Before 1991	2011
Net Contents	5 OZ	5 OZ
Functional Unit	1000 kg	1000 kg
Description	EPS Clamshell: 35915.5 g	F-flute Corrugated Clamshell: Unbleached Liners + Recycled Medium, 37% PCR: 78873.2 g

3.4 Inventory assessment

In this study, the data inputs are weights of the packaging components, and the input values are normalized according to the functional unit, 1000 kg or 1000 L. This allows comparisons even when the net contents vary.

Table 29 Weights and types of packaging components input to COMPASS based on the functional units. C1, C2, C3, C4, and C5 in the first row means component 1, component 2, component 3, component 4, and component 5. Weight unit is grams. CRB: Clay-coated recycled board, EPS: Expanded polystyrene, BP: Bleached paper

Sample	C1	C2	C3	C4	C5
1	CRB				
1.1	202500.0				
1.2	203970.6				
2	CRB				
2.1	153964.8				
2.2	145033.1				
3	CRB				
3.1	88000.0				
3.2	67205.9				
4	CRB	CRB	PVC/PLA	LDPE	
4.1	93333.3	4313.7	2745.1	13725.5	
4.2	75294.1	4117.6	1568.6	14117.6	
5	Glass				
5.1	898949.6				
5.2	724050.6				
6	Glass/Steel	Steel	BP		
6.1	538823.5	26176.5	882.4		
6.2	120221.3	20000.0	4918.0		
7	Glass/PETE	Steel/PP	Aluminum	BP	
7.1	531989.9	8816.1		755.7	
7.2	78085.6	36272.0	503.8	1007.6	
8	Glass	Aluminum/PP	BP		
8.1	533826.6	3171.2	3382.7		
8.2	509302.3	5074.0	2959.8		
9	Glass/PETE	Steel/PP	LPB/Aluminum	BP/PP	
9.1	684117.6	25588.2	5588.2	882.4	
9.2	61894.3	29074.9	1321.6	1982.4	
10	Glass/SBS	LDPE	PP	LDPE	LDPE
10.1	454334.0		8773.8		
10.2	36349.8	1135.9	914.3	685.7	342.9

Table 29 (Cont'd)

Sample	C1	C2	C3	C4	C5
11	Aluminum				
11.1	52542.4				
11.2	39154.9				
12	Aluminum				
12.1	53107.3				
12.2	37464.8				
13	Steel/HDPE	LDPE/PP	Aluminum		
13.1	189305.4	14994.5			
13.2	142842.5	22903.9	2965.2		
14	PETE	PP/Aluminum	PP	PP	
14.1	49471.5	3382.7	13530.7	634.2	
14.2	51923.7	4651.2		507.6	
15	PETE	PP	Aluminum	PP	
15.1	132158.6	65638.8	2643.2	5286.3	
15.2	124096.4	58232.9	2409.6	4417.7	
16	PETE	PP	Aluminum	BP	BP
16.1	62549.0	29411.8	784.3		3137.2
16.2	51372.5	19215.7	1372.5	1176.5	2941.2
17	PP				
17.1	30650.5				
17.2	31753.0				
18	PP	Aluminum			
18.1	57709.3	3083.7			
18.2	41176.5	3529.4			
19	PETE	PP	PP		
19.1	31258.5	6224.6	676.6		
19.2	30717.2	4465.5	676.6		
20	HDPE	HDPE	HDPE	BP	
20.1	63365.0	7327.0	1899.6	542.7	
20.2	60000.0	7647.1			

Table 29 (Cont'd)

Sample	C1	C2	C3	C4	C5
21	EPS/Corrugated Board				
21.1	25233.6				
21.2	53738.3				
22	EPS/Corrugated Board				
22.1	24242.4				
22.2	57070.7				
23	EPS/Corrugated Board				
23.1	35915.5				
23.2	78873.2				

Based on the data inputs shown in Tables 6 to 28, the process data were assessed by life cycle phase such as manufacture, conversion, distribution, and end-of-life. Process data, such as the production of chemicals, fuels, energy and power, is industry-average data. Data in COMPASS were obtained from all major industry associations working in the packaging supply chain (Mistry 2010a).

COMPASS has three database sets based on geographic regions, the U.S., Canada and Europe. The inventory database used for this study is the U.S dataset, since all packaging samples investigated in this study were produced and distributed in the United States. End-of-life of different materials and packaging types are based on the U.S. EPA MSW Facts and Figures report (Mistry 2010a).

The National Renewable Energy Laboratory in the Department of Energy controls the U.S. LCI (USLCI) database. Average data in industry submitted by industry associations are validated before they are included in the USLCI. However, the USLCI is incomplete, and processes of collection or verification are still ongoing (Mistry 2010a).

Due to this incompleteness, the U.S dataset in COMPASS uses a hybrid approach that is composed of process-level data from the USLCI combined with substitute data from Ecoinvent, which is the Swiss life cycle inventory database. Specifically, COMPASS uses data from Ecoinvent for the conversion and end-of-life phases (Mistry 2010a).

In Compass, the end-of-life phase of packages composed of recycling, waste to energy, landfill, composting, incineration, and litter and the end-of-life percentage is different as the type of packages, as shown in Table A1 in Appendix B.

3.5 Life cycle impact assessment

Even though COMPASS has a total of eight metrics, only five metrics were used in this study to focus on the energy and resource consumption and global warming gas emissions, because of their growing importance to the global environment, politics, and economy. The five life cycle impact metrics used were fossil fuel consumption, water consumption, biotic and mineral resources consumption, and greenhouse gas emissions. The impact category is a class representing environmental issues of concern into which life cycle inventory results may be assigned. Table 30 shows a brief explanation of the five impact indicators used in this study.

Table 30 Five life cycle impact metrics used in this study.

Impact Category	Description	Unit
Fossil Fuel Consumption	A measure of the quantity of fossil fuel consumed.	MJ
Water Consumption	A measure of the quantity of surface water and groundwater required.	L
Biotic Resource Consumption	A measure of the quantity of biotic resources required.	m^3
Mineral Consumption	A measure of the quantity of mineral resources required.	kg
Greenhouse Gas Emission	A measure of greenhouse gas emissions, such as CO_2 and methane.	kg CO_2 Equivalent

The metrics used by COMPASS were established in a stakeholder process including participation from across the packaging supply chain. The basis comes from MERGE™, originally developed by the Environmental Defense Fund. ISO 14044 sections 4.4.2.2.1 through 4.4.2.2.4 were used to guide the metrics development process (Mistry 2010a).

The fossil fuel consumption indicator is "a measure of the quantity of fossil fuel consumed to produce packaging, reported in mega joules per kilogram (MJ/kg) of packaging material" (Mistry 2010b, p. 12). This indicator focuses on the fossil fuel resources consumed for the production of the material. It provides an incentive for efficient use of fossil fuel-based resources and an incentive to use renewable or alternative sources of energy and resources. The consumption of 1 MJ of coal is considered to be the same as 1 MJ of crude oil or 1 MJ of natural gas. The algorithm of this metric used in COMPASS is shown in Table 31.

Table 31 COMPASS algorithm of fossil fuel consumption metric (Mistry 2010b, p. 12).

Algorithm	Description
$\boldsymbol{F = \sum e_i x_i}$ $i = 1 \ldots m$	F = the fossil fuel resources consumed in MJ per gram of packaging material x = the life cycle inventory flows of fossil fuel resource types in kilograms per kilogram of packaging material m = the number of different flows of fossil fuel resource types e = a vector of heating values in MJ/kg, for fossil fuels Data sources are from life cycle inventory data.

The water consumption indicator is "a measure of the quantity of surface water and groundwater required to produce packaging, reported in liters per kilogram (l/kg) of packaging material" (Mistry 2010b, p. 13). This indicator does not involve non-consumptive sources of water such as water used for navigation. Table 32 shows the algorithm for the water consumption metric in COMPASS.

Table 32 COMPASS algorithm of water consumption metric (Mistry 2010b, p. 13).

Algorithm	Description
$\boldsymbol{W = \sum x_i}$ $i = 1 \ldots m$	W = the surface water and groundwater consumed in liters per kilogram of packaging material x = the life cycle inventory flows of surface water and groundwater in liters per kilogram of packaging material m = the number of different flows of surface water and groundwater Data sources are from life cycle inventory data.

The biotic resource consumption indicator is "a measure of the quantity of biotic resources required to produce the packaging, reported in cubic meters per kilogram (m^3/kg) of packaging material" (Mistry 2010b, p. 13). Table 33 indicates the algorithm of biotic resource consumption in COMPASS.

Table 33 COMPASS algorithm of biotic resources consumption metric (Mistry 2010b, p. 13).

Algorithm	Description
$\boldsymbol{B = \sum x_i}$ $i = 1 \ldots m$	B = the biotic resources consumed in cubic meters per kilogram of packaging material x = the life cycle inventory flows of biotic resources in cubic meters per kilogram of packaging material m = the number of different flows of biotic resources Data sources are from life cycle inventory data.

The mineral consumption indicator is "a measure of the quantity of mineral resources required to produce the packaging, reported in kilogram per kilogram (kg/kg) of packaging material" (Mistry 2010b, p. 14). This indicator includes all non-fuel mineral "raw material" input flows in the life cycle inventory, and applicable nuclear fuel sources such as uranium. The algorithm of this metric is shown in Table 34.

Table 34 COMPASS algorithm of mineral resources consumption metric (Mistry 2010b, p. 14).

Algorithm	Description
$\boldsymbol{M = \sum x_i}$ $i = 1 \ldots m$	M = the mineral resources consumed in kilogram per kilogram of packaging material x = the life cycle inventory flows of mineral resources in kilogram per kilogram of packaging material m = the number of different flows of mineral resources Data sources are from life cycle inventory data.

The greenhouse gas emission indicator is "a measure of the quantity of green house gases (GHG) emitted during the production of the materials used in the packaging, reported in carbon dioxide equivalents/kilogram (kg CO_2 eq./kg) of packaging material" (Mistry 2010b, p. 14). These emissions are causing an increase in the absorption of radiation emitted by the earth, magnifying the natural greenhouse effect. Table 35 shows a brief algorithm of how the GHG impact category is measured in the COMPASS LCA.

Table 35 COMPASS algorithm of greenhouse gas emission metric (Mistry 2010b, p. 14).

Algorithm	Description
$\boldsymbol{G = \sum gwp_i x_i}$ $i = 1 \ldots m$	G = the greenhouse gas emissions generated per kilogram of packaging material x = the life cycle inventory flows of greenhouse gas emissions in kilogram per kilogram of packaging material m = the number of different flows of greenhouse gas emissions gwp = a vector of global warming potentials in CO_2 equivalents/kilogram of GHG emission to air Data sources are from life cycle inventory data.

3.6 Interpretation

There are various interpretation methods for LCA, such as contribution analysis, comparative analysis, perturbation analysis, uncertainty analysis, and discernibility analysis.

However, only the contribution analysis and the comparative analysis were performed in this study, since the purpose of this study was to compare the old packages to the current ones and by investigating the environmental impact factors of each system.

Contribution analysis is performed at the level of characterization. In this study, the model consisted of three phases: manufacturing, conversion, and end-of-life. Contribution analysis is applied to find how those phases contribute the environmental burden for each LCA scenario. The share of all life cycle phases in the total impacts is calculated and contributions of life cycle phases are identified.

After the contribution analysis, a comparative analysis was performed to determine which package type had more environmental burdens, compared to the alternative. Thus, comparative analysis indicates numerically which packaging is environmentally superior in order to clearly compare the results of the LCA. Comparative analysis is performed for each impact indicator metric, and the final evaluation considered comparative results of all indicators.

CHAPTER 4: RESULTS AND DISCUSSIONS

Life cycle metrics, which are provided in impact categories, are estimated measures of the environmental impacts resulting from all of the industrial activity connected to the production of a package. Life cycle metrics of the COMPASS software analyzes the results of the LCA in four phases: manufacture, conversion, distribution and end of life. These metrics indicate the environmental burdens in total and for each phase. A positive calculated number means that the phase causes a net environmental impact, while a negative value expresses a net environmental benefit which is interpreted as a credit. This study covered three phases of life cycle: manufacture, conversion, and end-of-life.

Based on materials of the old packages, there are five packaging categories: cartons, glass, metal, plastics, and McDonalds (as a separate category). Each category has several Sample Groups that include an old package and a current package.

The LCA are based on two analysis methods: comparative analysis and contribution analysis. The results are organized by each packaging category.

Comparative analysis was performed to determine the more environmentally sustainable package between the old one and the current one. Each comparative analysis was presented using five life cycle impact indicators: greenhouse gas emissions, fossil fuel consumption, water consumption, biotic resources consumption, and mineral resources consumption. Five figures in Appendix A for each category show the comparisons.

Contribution analysis was performed to investigate which phase is the main factor in the life cycle impacts of each package. A table for each Sample Group shows the contribution factors of each impact life cycle impact. Figures that show the contribution to life cycle phases for all Sample Groups are in the Appendix A.

Appendix B shows the end-of-life percentage of packages such as recycling, waste to energy, landfill, composting, incineration and litter.

4.1 Category 1: Paperboard cartons

Figures 55 to 59 show the comparisons of the LCA results between the old package and the current package for the Sample Groups in Category 1. Figure 55 is for fossil fuel consumption, Figure 56 is for water consumption, Figure 57 is for biotic resource consumption, Figure 58 is for mineral resource consumption, and Figure 59 is for greenhouse gas (GHG) emissions.

In Sample Group 1 for Kellogg's Corn Flakes cereal cartons, the current package demanded more fossil fuel, water, biotic resources, and mineral resources and generates more GHG than the old package. This is not surprising since it was the only Sample Group in the carton category where the current carton was heavier than the old one.

The old packages of Sample Groups 2 for Ritz-Crackers, 3 for Post Grape-Nuts, and 4 for Quaker Oats demand more fossil fuel, water, biotic resources, and mineral resources and generate more GHG than the current packages. The primary reason for these results is the lighter weight (in general) of the current packages' paperboard, since the materials of both packages were almost the same. The heavier paperboard cartons consume more resources and generate more GHG.

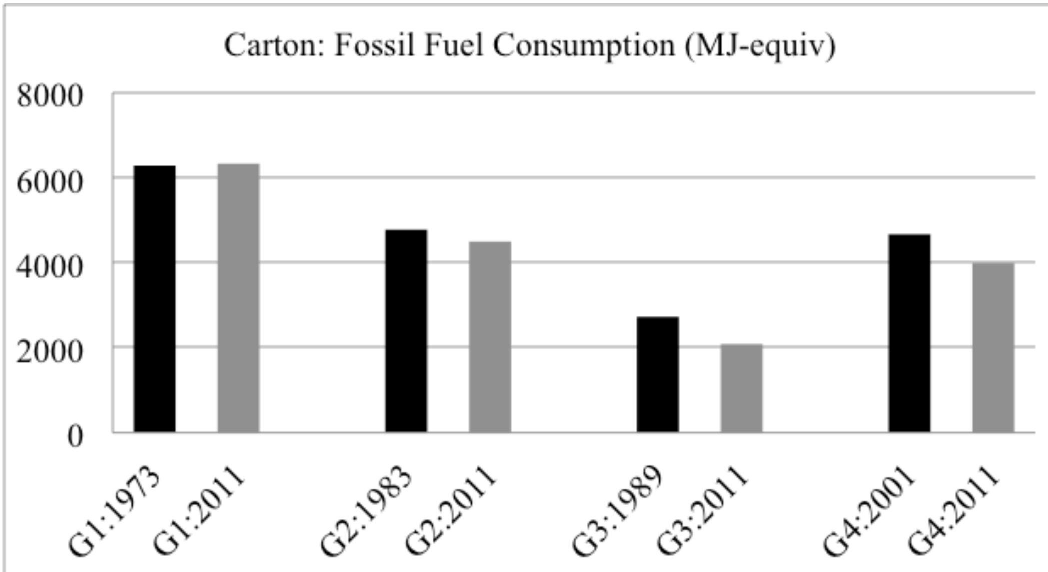

Figure 55 Fossil fuel consumption of Sample Groups in Category 1

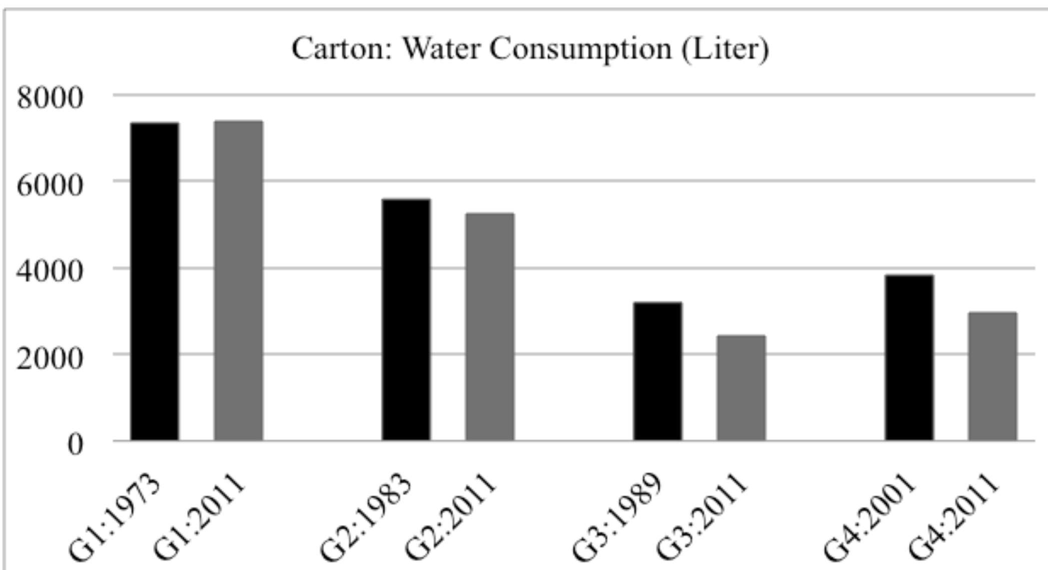

Figure 56 Water consumption of Sample Groups in Category 1

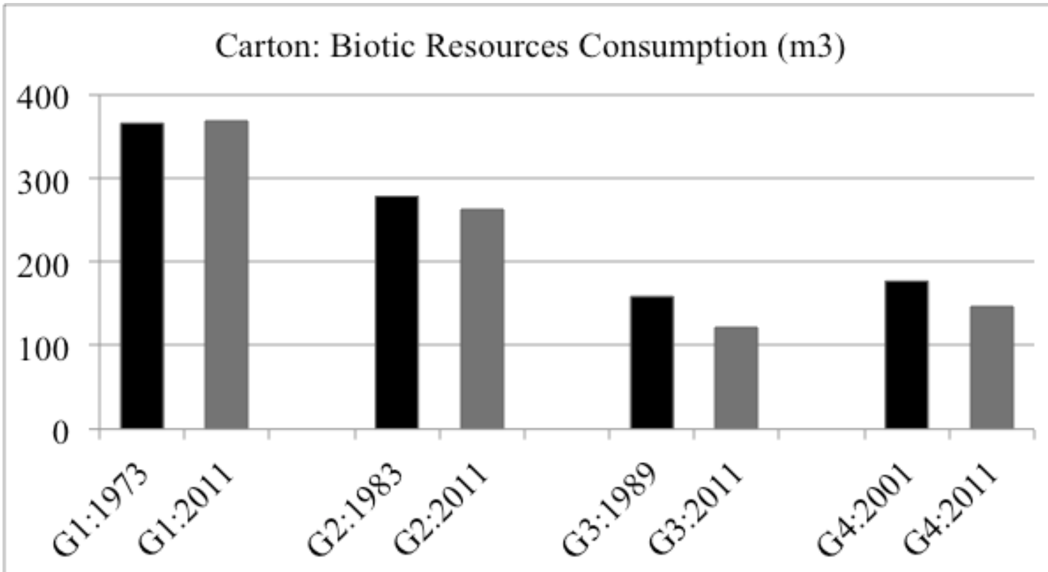

Figure 57 Biotic resources consumption of Sample Groups in Category 1

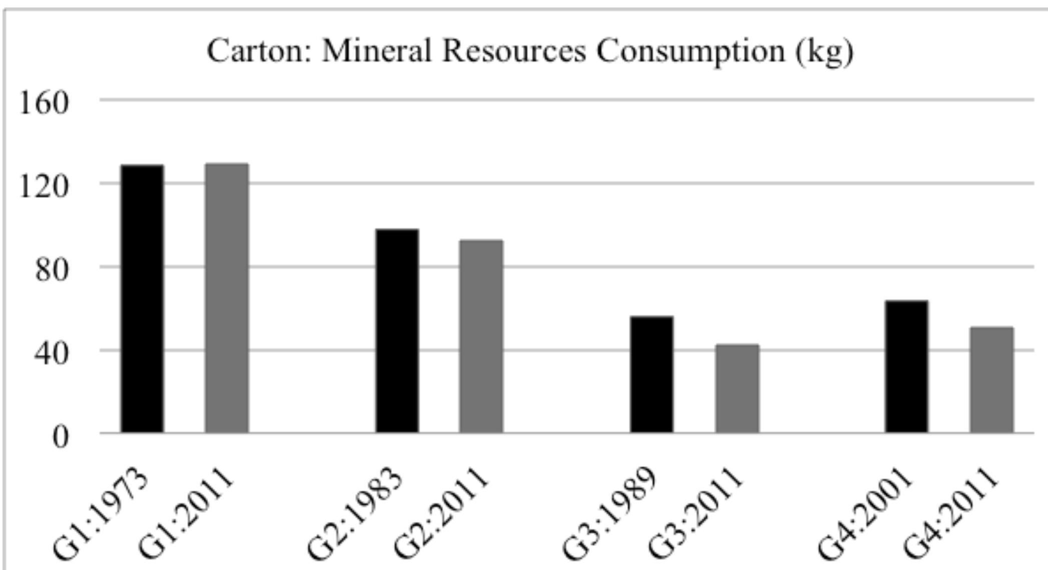

Figure 58 Mineral resources consumption of Sample Groups in Category 1

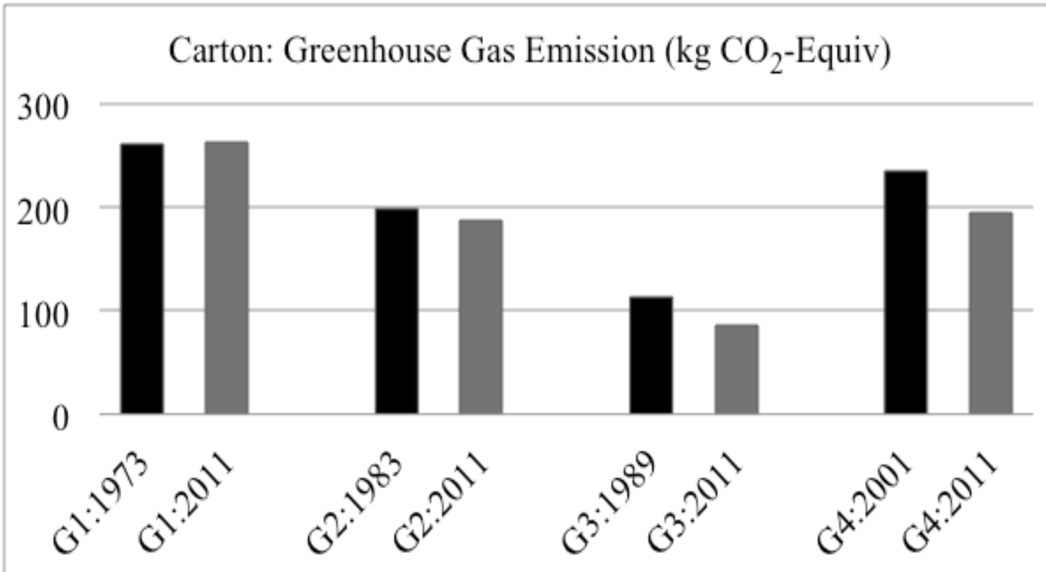

Figure 59 Greenhouse gas emissions of Sample Groups in Category 1

As shown in the following sections, which detail the results from each sample group, manufacturing of the paperboard was found to be the primary contributor to the consumption of fossil fuel, water, mineral and biotic resources. This is because of the trees harvested to make paperboard, the clay coating, and the high energy and water usage in the pulping process, including the repulping process for recycled paperboard. The conversion process is a secondary contributor to resource consumption because the scoring, cutting and gluing are more mechanical than resource-intensive.

The primary GHG contributor is the end-of-life phase, because paperboard generates GHG as it decomposes. End-of-life results for paperboard products vary considerably depending on assumptions about decomposition. At maximum experimental decomposition levels, the overall effect of the estimated GHG additions and credits from end-of-life management is a large net increase in GHG for paperboard products. At lower decomposition rates, the net end-of-life GHG for paperboard products is much smaller, since less methane is released and more carbon is sequestered in undecomposed material. If the paperboard does not decompose, no methane is produced and all the biomass carbon in the paperboard product is sequestered, resulting in a large carbon sequestration credit (Franklin 2011). The carbon sequestration is the process through which carbon dioxide from the atmosphere is absorbed by trees and plants through photosynthesis, and stored as carbon in biomass: tree trunks, branches, foliage and roots, and soils (EPA 2008). It also affected by whether methane is collected and provides a fuel credit.

The manufacturing phase has a negative GHG value, which means the phase has a net CO_2 sink, which occurs when carbon sequestration is greater than carbon releases over the manufacturing period. The negative value is interpreted as a credit or avoidance of GHG emissions or resource consumption in LCA and it is primarily related to growing trees. Net GHG emissions are calculated taking into account the CO_2 equivalent sequestered by trees during their growth and they can be counted by means of the CO_2 equivalent credit which is a negative value.

The end-of-life phase is also a negative source of fossil fuel consumption for both packages since the material can be recycled or recovered from waste to energy, representing a credit of fossil fuel that can be avoidance of fuel use. As Table A1 in Appendix B indicates, by using COMPASS, the end-of-life phase of folding cartons made of recycled folding boxboard composed of 27.3% recycling, 12.6% waste to energy, and 60.1% landfill.

The end-of-life phase for paperboard cartons has the lowest impact on water, biotic, and mineral resource consumption.

4.1.1 Contribution for Sample Group 1

Table 36 shows the LCA results of Sample Group 1 for Kellogg's Corn Flakes cereal cartons based on each phase. Figures A.1 to A.5 in the Appendix A show contribution of each phase to each of each life cycle impact indicator for Sample Group 1.

Table 36 Total life cycle impacts in impact categories of Sample Group 1.

Impact Indicators	Phases	1973	2011
Fossil Fuel Consumption (MJ-equiv)	Manufacture	4,611.00	4,644.50
	Conversion	1,758.80	1,771.60
	End of Life	-84.60	-85.21
Water Consumption (l)	Manufacture	6,413.30	6,459.90
	Conversion	932.26	939.03
	End of Life	6.75	6.80
Biotic Resource Consumption (m^3)	Manufacture	345.86	348.37
	Conversion	20.40	20.55
	End of Life	-0.06	-0.06
Mineral Consumption (kg)	Manufacture	117.78	118.63
	Conversion	10.47	10.55
	End of Life	0.23	0.23
GHG Emission (kg C02-Equiv)	Manufacture	-76.31	-76.86
	Conversion	95.97	96.66
	End of Life	241.69	243.44

4.1.2 Contribution for Sample Group 2

Table 37 shows the LCA results of Sample Group 2 for Ritz-Crackers cartons based on each phase. Figures A.6 to A.10 in the Appendix A show the contribution of each phase to each life cycle impact indicator for Sample Group 2.

Table 37 Total life cycle impacts in impact categories of Sample Group 2.

Impact Indicators	Phases	1983	2011
Fossil Fuel Consumption (MJ-equiv)	Manufacture	3,505.90	3,302.50
	Conversion	1,337.30	1,259.70
	End of Life	-64.32	-60.59
Water Consumption (l)	Manufacture	4,876.20	4,593.30
	Conversion	708.81	667.70
	End of Life	5.14	4.84
Biotic Resource Consumption (m^3)	Manufacture	262.96	247.71
	Conversion	15.51	14.61
	End of Life	-0.05	-0.04
Mineral Consumption (kg)	Manufacture	89.55	84.36
	Conversion	7.96	7.50
	End of Life	0.17	0.16
GHG Emission (kg CO_2-Equiv)	Manufacture	-58.02	-54.65
	Conversion	72.97	68.73
	End of Life	183.76	173.10

4.1.3 Contribution for Sample Group 3

Table 38 shows the LCA results of Sample Group 3 for Post Grape-Nuts cereal cartons based on each phase. Figures A.11 to A.15 in the Appendix A show the contribution of each phase to each life cycle impact indicator for Sample Group 3.

Table 38 Total life cycle impacts in impact categories of Sample Group 3.

Impact Indicators	Phases	1989	2011
Fossil Fuel Consumption (MJ-equiv)	Manufacture	2,003.80	1,530.30
	Conversion	764.34	583.73
	End of Life	-36.76	-28.08
Water Consumption (l)	Manufacture	2,787.00	2,128.40
	Conversion	405.13	309.40
	End of Life	2.94	2.24
Biotic Resource Consumption (m^3)	Manufacture	150.30	114.78
	Conversion	8.87	6.77
	End of Life	-0.03	-0.02
Mineral Consumption (kg)	Manufacture	51.18	39.09
	Conversion	4.55	3.48
	End of Life	0.10	0.08
GHG Emission (kg CO_2-Equiv)	Manufacture	-33.16	-25.33
	Conversion	41.70	31.85
	End of Life	105.03	80.21

4.1.4 Contribution for Sample Group 4

Table 39 shows the LCA results of Sample Group 4 for Quaker Oats cartons based on each phase. Figures A.16 to A.20 in the Appendix A show the contribution of each phase to each life cycle impact indicator for Sample Group 4.

Table 39 Total life cycle impacts in impact categories of Sample Group 4.

Impact Indicators	Phases	2001	2011
Fossil Fuel Consumption (MJ-equiv)	Manufacture	3,554.40	3,027.70
	Conversion	1,170.10	1,013.30
	End of Life	-49.47	-45.06
Water Consumption (l)	Manufacture	3,342.40	2,569.10
	Conversion	491.52	407.89
	End of Life	3.91	1.71
Biotic Resource Consumption (m^3)	Manufacture	166.87	137.61
	Conversion	10.19	8.31
	End of Life	-0.04	-0.03
Mineral Consumption (kg)	Manufacture	57.69	46.29
	Conversion	5.40	4.46
	End of Life	0.31	0.10
GHG Emission (kg CO_2-Equiv)	Manufacture	-2.03	-3.67
	Conversion	68.41	59.78
	End of Life	168.57	138.04

4.2 Category 2: Glass bottles and jars

Figures 60 to 64 show the comparisons of the LCA results between the old package and the current package for the Sample Groups in Category 2. Figure 60 is for the fossil fuel consumption, Figure 61 is for the water consumption, Figure 62 is for the biotic resource consumption, Figure 63 is for the mineral resource consumption, and Figure 64 is for the greenhouse gas (GHG) emissions. The conversion phases of the glass packages have no data, since COMPASS includes the conversion phase in manufacturing for glass materials.

This category has glass bottles, but four of the samples represent a transition from glass to PET, aluminum and paperboard. In the strictly glass to glass samples, there was not much change in the results of every indicator. If the package changed from glass to PET, fossil fuel consumption and GHG emissions increased. If the glass jar was changed from glass to a paperboard carton, only the biotic resource consumption increased. Paperboard's lower energy requirements during production affect these results. This is because the paperboard consumes trees, which need biotic resources, whereas the glass is almost abiotic material. If the glass jar was changed from glass to a steel can, all resource consumption and GHG emissions decreased. The lower resource consumption of steel production and high recycling rate of the steel can affect this result.

In cases of Sample Group 5 for Coca-Cola bottles, Sample Group 6 for Campbell's Soup packages, and Sample Group 8 for Heinz Apple cider bottles, the old package demanded more fossil fuel, water, biotic resources, and mineral resources and generated more GHG than the current package.

In case of Sample Group 7 for Heinz Ketchup bottles, the old package demanded more water, biotic resources, and mineral resources and generated more GHG than the current package. The current package demanded more fossil fuel consumption than the old package.

In case of Sample Group 9 for Kraft Romano Cheese packages, the old package demanded more water, biotic resources, and mineral resources, while the current package demanded more fossil fuel and generated more GHG than the old package.

In case of Sample Group 10 for Tropicana Orange Juice packages, the old package demanded more fossil fuel, water, and mineral resources and generated more GHG than the current package, while it demanded less biotic resources than the current one.

The main reasons for the results for Sample Group 5 and Sample Group 8 are the weights of the glass jars or bottles, since both packages are both glass.

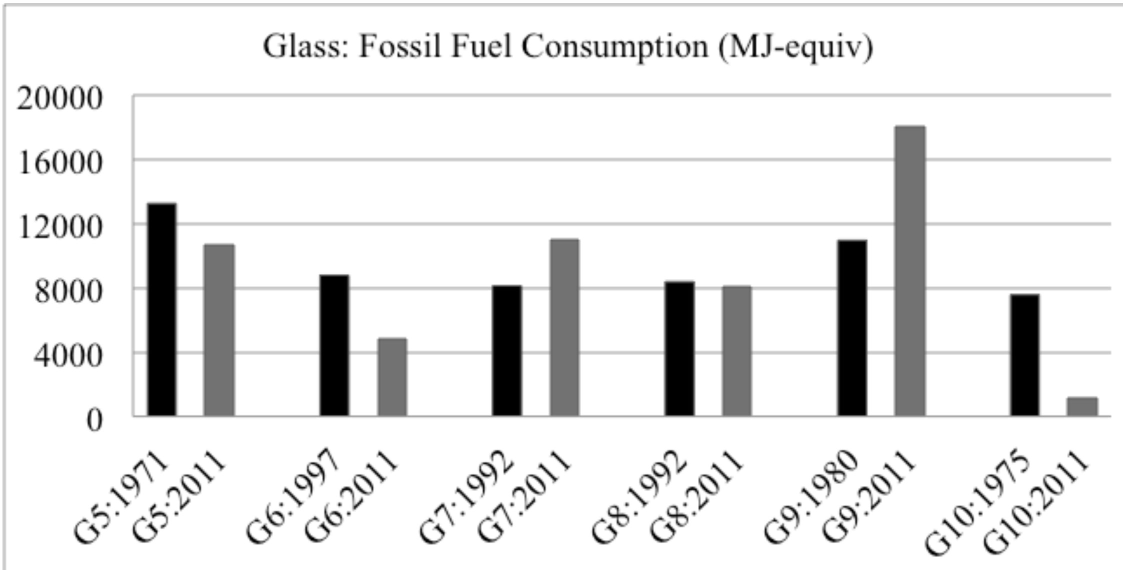

Figure 60 Fossil fuel consumption of Sample Groups in Category 2

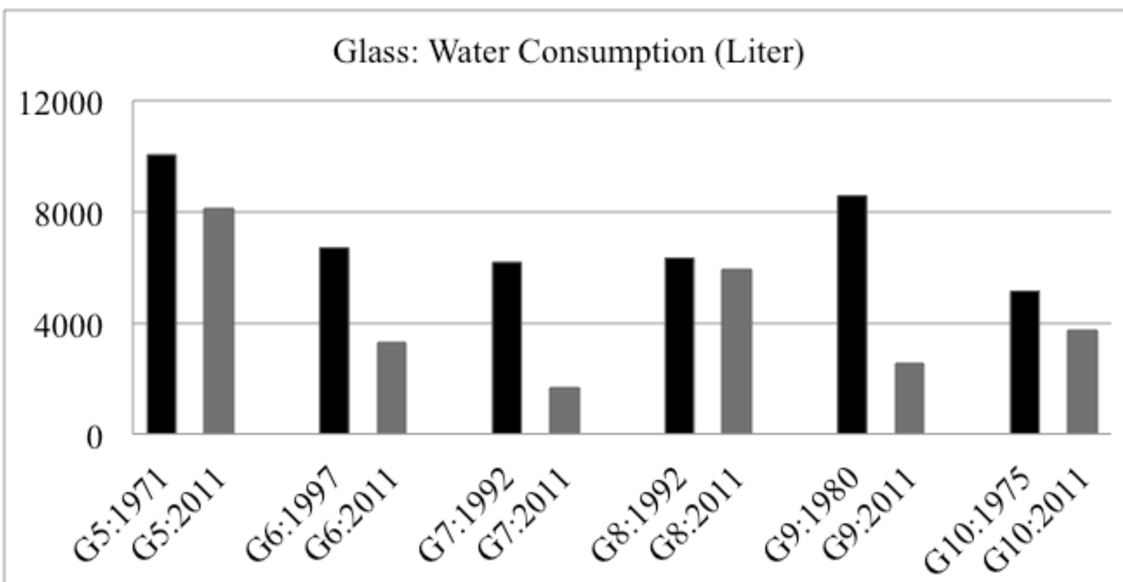

Figure 61 Water consumption of Sample Groups in Category 2

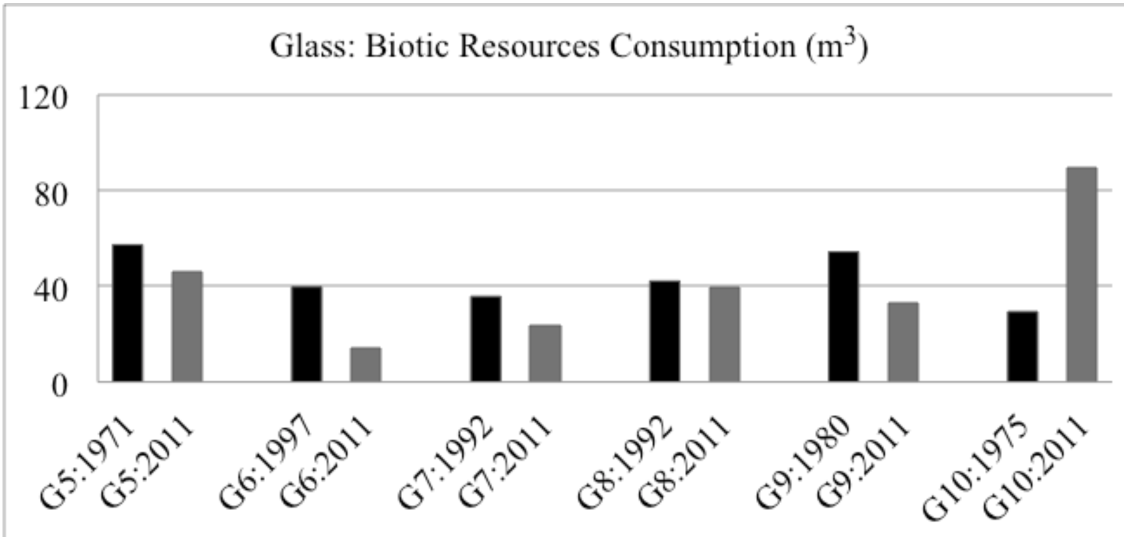

Figure 62 Biotic resources consumption of Sample Groups in Category 2

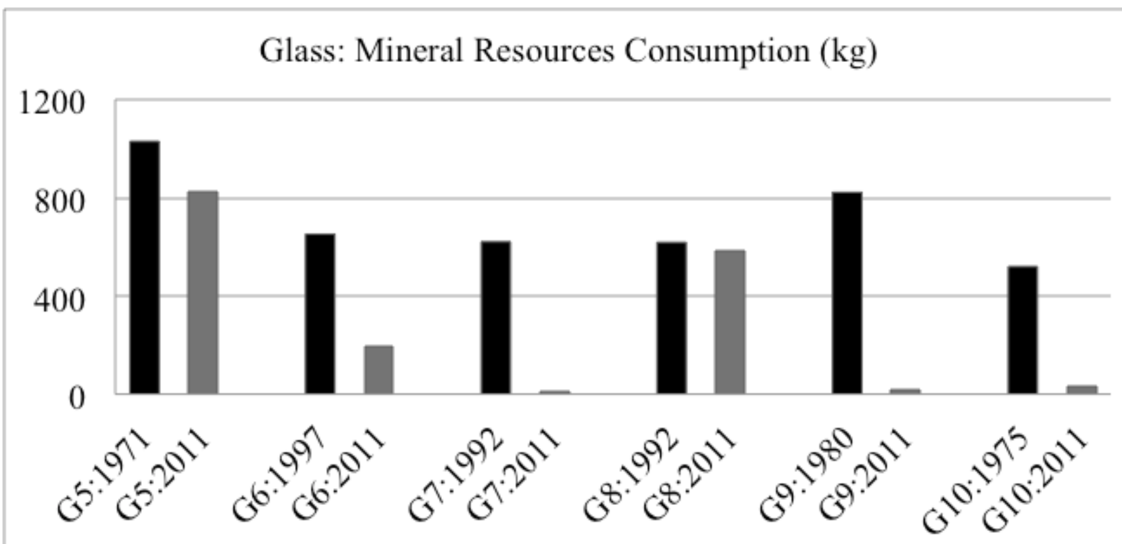

Figure 63 Mineral resources consumption of Sample Groups in Category 2

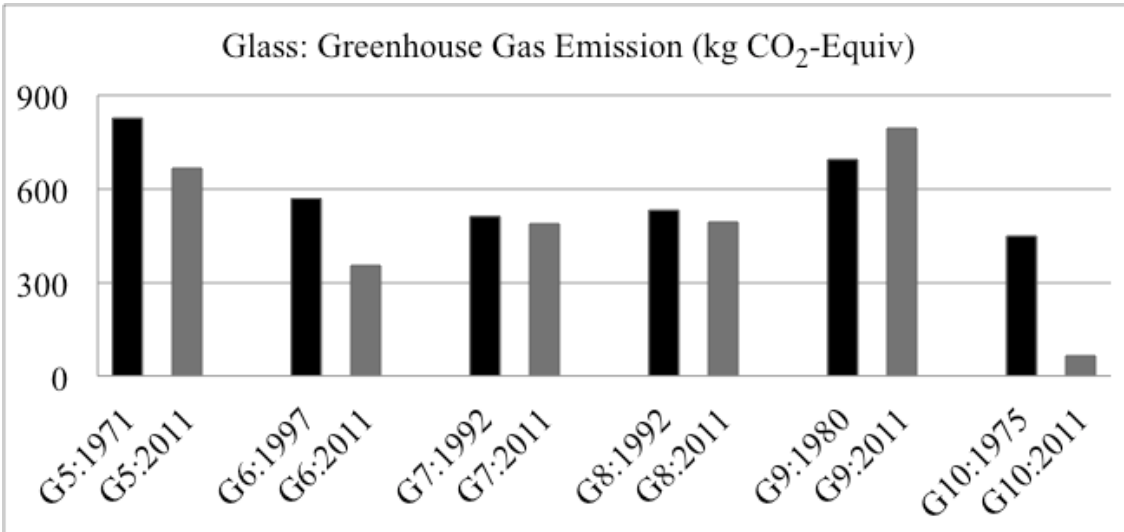

Figure 64 Greenhouse gas emissions of Sample Groups in Category 2

As shown in the following sections, which show details of the results from each sample group, manufacturing of the glass bottles was found to be the primary contributor to the consumption of fossil fuel, water, mineral and biotic resources and GHG emissions. This is because the silica production consumes these resources. The end-of-life phase for glass bottles has considerably less impact, because glass is highly recycled and does not biodegrade. The conversion phase of glass is included in the manufacturing phase.

4.2.1 Contribution for Sample Group 5

Table 40 shows the LCA results of Sample Group 5 for Coca-Cola Coke bottles based on each phase. Figures A.21 to A.25 in the Appendix A show the contribution of each phase to each life cycle impact indicator for Sample Group 5.

Table 40 Total life cycle impacts in impact categories of Sample Group 5.

Impact Indicators	Phases	1971	2011
Fossil Fuel Consumption (MJ-equiv)	Manufacture	13,053.00	10,513.00
	End of Life	162.77	131.10
Water Consumption (l)	Manufacture	9,907.30	7,979.70
	End of Life	145.43	117.14
Biotic Resource Consumption (m^3)	Manufacture	57.28	46.13
	End of Life	0.07	0.06
Mineral Consumption (kg)	Manufacture	1,028.20	828.16
	End of Life	0.06	0.05
GHG Emission (kg CO_2-Equiv)	Manufacture	813.60	655.30
	End of Life	12.85	10.35

Conversion of glass is included in manufacture.

4.2.2 Contribution for Sample Group 6

Table 41 shows the LCA results of Sample Group 6 for Campbell's Soup packages based on each phase. Figures A.25 to A.30 in the Appendix A show the contribution of each phase to each life cycle impact indicator for Sample Group 6.

Table 41 Total life cycle impacts in impact categories of Sample Group 6.

Impact Indicators	Phases	1997	2011
Fossil Fuel Consumption (MJ-equiv)	Manufacture	8,529.70	3,691.00
	Conversion	152.58	1,170.30
	End of Life	105.61	3.68
Water Consumption (l)	Manufacture	6,553.10	2,971.30
	Conversion	56.13	340.37
	End of Life	88.15	1.48
Biotic Resource Consumption (m^3)	Manufacture	39.64	13.98
	Conversion	0.06	0.50
	End of Life	0.04	0.00
Mineral Consumption (kg)	Manufacture	647.97	171.34
	Conversion	3.80	25.72
	End of Life	0.04	0.02
GHG Emission (kg CO_2-Equiv)	Manufacture	536.39	266.61
	Conversion	11.07	80.82
	End of Life	11.25	7.76

Conversion of glass is included in manufacture.

4.2.3 Contribution for Sample Group 7

Table 42 shows the LCA results of Sample Group 7 for Heinz Tomato Ketchup bottles based on each phase. Figures A.31 to A.35 in the Appendix A show the contribution of each phase to each life cycle impact indicator for Sample Group 7.

Table 42 Total life cycle impacts in impact categories of Sample Group 7.

Impact Indicators	Phases	1992	2011
Fossil Fuel Consumption (MJ-equiv)	Manufacture	7,969.10	8,742.20
	Conversion	51.40	2,385.50
	End of Life	104.29	-118.80
Water Consumption (l)	Manufacture	6,075.80	493.74
	Conversion	18.91	1,158.10
	End of Life	87.02	-12.98
Biotic Resource Consumption (m^3)	Manufacture	35.74	3.28
	Conversion	0.02	20.72
	End of Life	0.04	-0.08
Mineral Consumption (kg)	Manufacture	619.67	2.36
	Conversion	1.28	8.25
	End of Life	0.04	-0.01
GHG Emission (kg CO_2-Equiv)	Manufacture	498.29	300.59
	Conversion	3.73	160.32
	End of Life	9.20	29.07

Conversion of glass is included in manufacture.

4.2.4 Contribution for Sample Group 8

Table 43 shows the LCA results of Sample Group 8 for Heinz Apple Cider bottles based on each phase. Figures A.36 to A.40 in the Appendix A show the contribution of each phase to each life cycle impact indicator for Sample Group 8.

Table 43 Total life cycle impacts in impact categories of Sample Group 8.

Impact Indicators	Phases	1992	2011
Fossil Fuel Consumption (MJ-equiv)	Manufacture	8,251.10	7,875.10
	Conversion	33.20	125.92
	End of Life	104.93	93.75
Water Consumption (l)	Manufacture	6,233.70	5,810.90
	Conversion	6.41	21.30
	End of Life	88.24	82.82
Biotic Resource Consumption (m^3)	Manufacture	42.16	39.54
	Conversion	0.01	0.23
	End of Life	0.04	0.04
Mineral Consumption (kg)	Manufacture	618.54	585.21
	Conversion	0.08	0.20
	End of Life	0.05	0.04
GHG Emission (kg CO_2-Equiv)	Manufacture	516.26	468.90
	Conversion	2.68	8.52
	End of Life	12.78	13.29

Conversion of glass is included in manufacture.

4.2.5 Contribution for Sample Group 9

Table 44 shows the LCA results of Sample Group 9 for Kraft Romano Cheese packages based on each phase. Figures A.41 to A.45 in the Appendix A show the contribution of each phase to each life cycle impact indicator for Sample Group 9.

Table 44 Total life cycle impacts in impact categories of Sample Group 9.

Impact Indicators	Phases	1980	2011
Fossil Fuel Consumption (MJ-equiv)	Manufacture	10,681.00	14,429.00
	Conversion	152.11	3,781.30
	End of Life	132.59	-192.03
Water Consumption (l)	Manufacture	8,405.40	771.20
	Conversion	55.59	1,785.10
	End of Life	112.25	-20.77
Biotic Resource Consumption (m^3)	Manufacture	54.25	1.40
	Conversion	0.07	32.10
	End of Life	0.05	-0.13
Mineral Consumption (kg)	Manufacture	818.52	5.14
	Conversion	3.71	12.79
	End of Life	0.06	-0.01
GHG Emission (kg CO_2-Equiv)	Manufacture	661.83	495.28
	Conversion	11.24	254.47
	End of Life	21.06	45.93

Conversion of glass is included in manufacture.

4.2.6 Contribution for Sample Group 10

Table 45 shows the LCA results of Sample Group 10 for Tropicana Orange Juice packages based on each phase. Figures A.46 to A.50 in the Appendix A show the contribution of each phase to each life cycle impact indicator for Sample Group 10.

Table 45 Total life cycle impacts in impact categories of Sample Group 10.

Impact Indicators	Phases	1980	2011
Fossil Fuel Consumption (MJ-equiv)	Manufacture	7,281.70	840.97
	Conversion	213.33	372.05
	End of Life	79.89	-16.43
Water Consumption (l)	Manufacture	5,031.50	3,545.90
	Conversion	35.77	177.33
	End of Life	73.21	1.24
Biotic Resource Consumption (m^3)	Manufacture	28.97	85.68
	Conversion	0.39	3.82
	End of Life	0.03	-0.01
Mineral Consumption (kg)	Manufacture	519.68	29.39
	Conversion	0.34	1.97
	End of Life	0.03	0.04
GHG Emission (kg CO_2-Equiv)	Manufacture	425.31	-16.70
	Conversion	14.10	21.01
	End of Life	9.64	61.66

Conversion of glass is included in manufacture.

4.3 Category 3: Metal cans

Figures 65 to 69 show the comparisons of the LCA results between the old package and the current package of the Sample Groups in Category 3. Figure 65 is for fossil fuel consumption, Figure 66 is for water consumption, Figure 67 is for biotic resource consumption, Figure 68 is for mineral resource consumption, and Figure 69 is for greenhouse gas (GHG) emissions.

In cases of Sample Group 11 for Coca-Cola Coke cans and Sample Group 12 for Coca-Cola Diet Coke cans, the old aluminum cans demanded more fossil fuel, water, biotic resources, and mineral resources and generated more GHG than the current package. The primary reason for this is the lighter weight of the new packages.

In case of Sample Group 13, Maxwell House Coffee packages, the current HDPE jar demanded more water, biotic resources and generates less GHG than the old steel can, whereas the steel can demanded more mineral resource consumption. This is because the HDPE jar consumed a relatively large amount of energy resources and generates GHG during its manufacturing and conversion stage, such as production of resins/pellets, and the molding process.

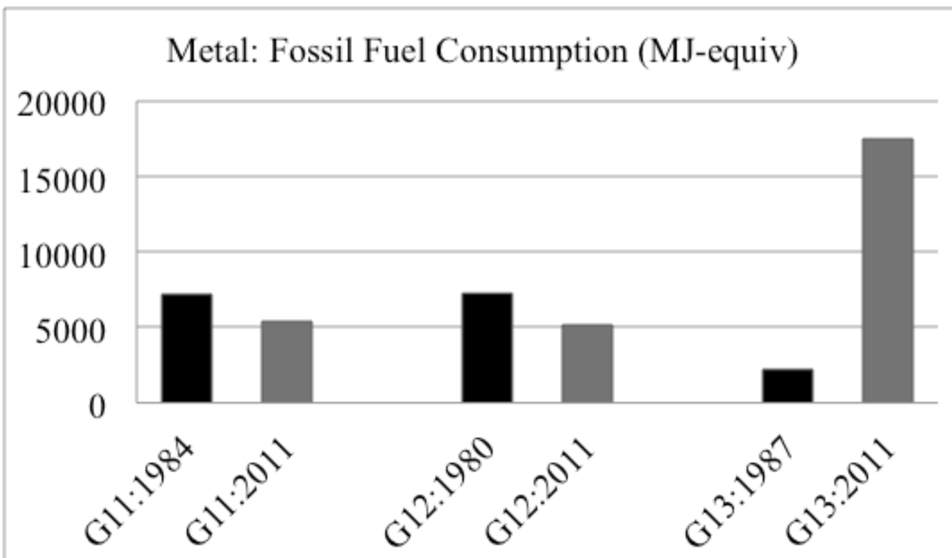

Figure 65 Fossil fuel consumption of Sample Groups in Category 3

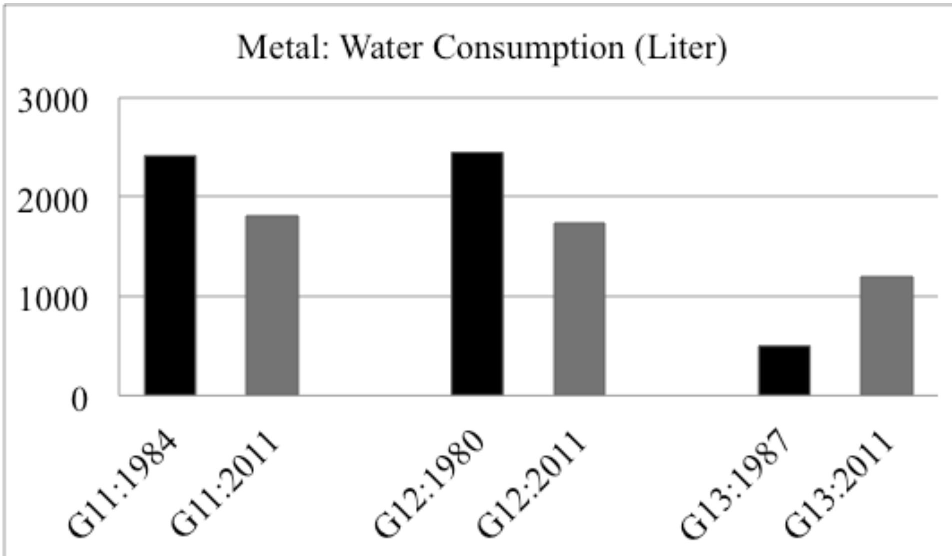

Figure 66 Water consumption of Sample Groups in Category 3

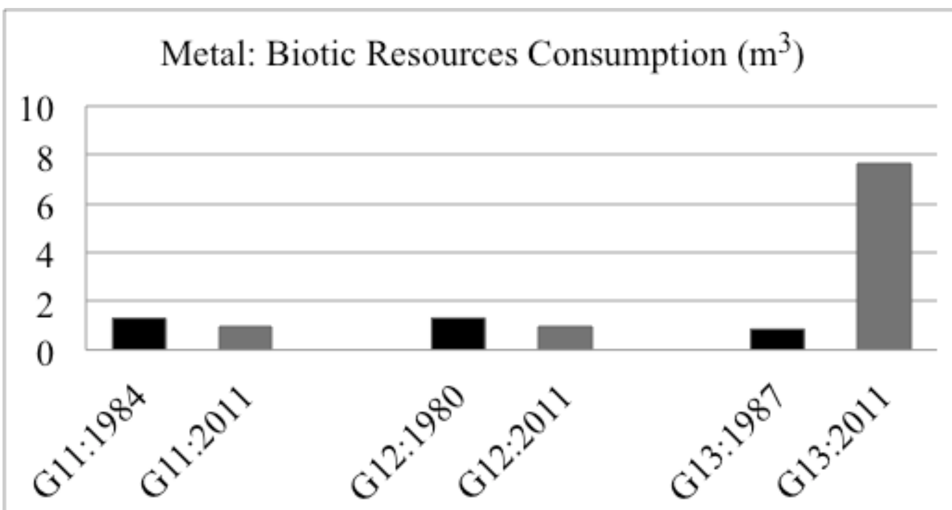

Figure 67 Biotic resources consumption of Sample Groups in Category 3

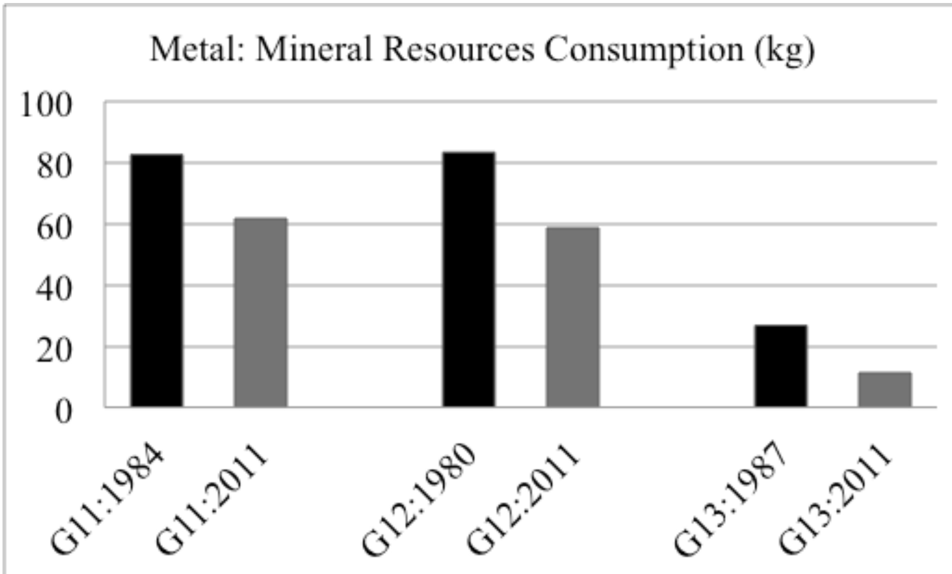

Figure 68 Mineral resources consumption of Sample Groups in Category 3

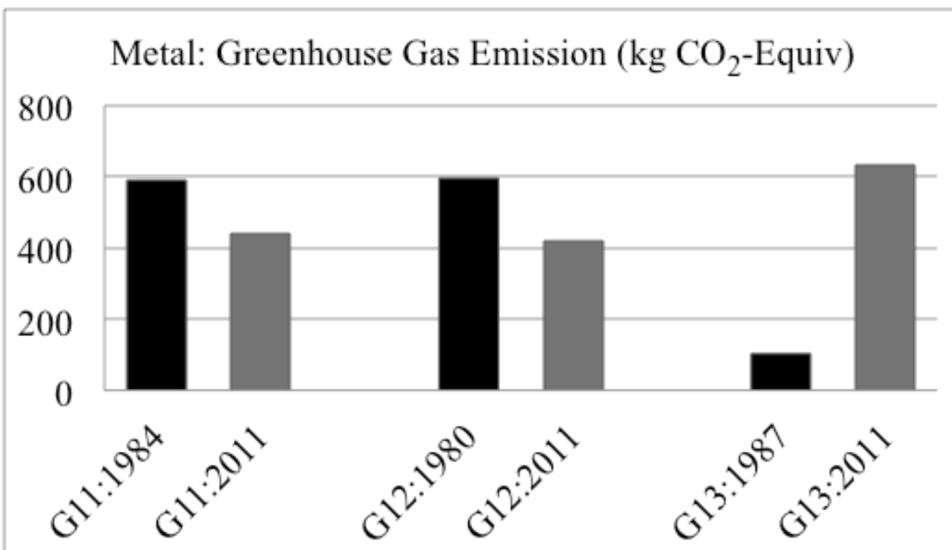

Figure 69 Greenhouse gas emissions of Sample Groups in Category 3

As shown in the following sections, which show details the results from each sample group, manufacturing of the steel can was found to be the primary contributor to the consumption of fossil fuel, water, biotic resource, and mineral resource and GHG emissions. This is because extracting bauxite and producing alumina powder mostly demand them and generate it.

The manufacturing phase of the HDPE jar for the current package is also highest contributor to the consumption of fossil fuel and GHG emissions. This means that production of resins/pellets demanded more fossil fuel consumption and generated more GHG emissions than the conversion process such as injection molding.

The end-of-life phase is a negative source of fossil fuel consumption, water consumption, biotic resource consumption, and mineral resource consumption for both packages since the material can be recycled or recovered from waste to energy, representing a credit of fossil fuel/other resources that can be avoided of use. As Table A1 in Appendix B indicates, by using COMPASS, the end-of-life phase of glass bottles for beverages composed of 34.5% recycling, 12.6% waste to energy, and 52.9% landfill. The end-of-life of glass jars composed of 14.8% recycling, 12.6% waste to energy, and 72.6% landfill.

4.3.1 Contribution for Sample Group 11

Table 46 shows the LCA results of Sample Group 11 for Coca-Cola Coke cans based on each phase. Figures A.51 to A.55 in the Appendix A show the contribution of each phase to each life cycle impact indicator for Sample Group 11.

Table 46 Total life cycle impacts in impact categories of Sample Group 11.

Impact Indicators	Phases	1984	2011
Fossil Fuel Consumption (MJ-equiv)	Manufacture	6,692.20	4,987.00
	Conversion	501.71	373.88
	End of Life	7.28	5.43
Water Consumption (l)	Manufacture	2,324.40	1,732.20
	Conversion	94.48	70.41
	End of Life	2.95	2.19
Biotic Resource Consumption (m^3)	Manufacture	1.09	0.81
	Conversion	0.20	0.15
	End of Life	0.00	0.00
Mineral Consumption (kg)	Manufacture	81.28	60.57
	Conversion	1.21	0.90
	End of Life	0.10	0.07
GHG Emission (kg CO_2-Equiv)	Manufacture	552.54	411.76
	Conversion	37.51	27.95
	End of Life	0.58	0.43

4.3.2 Contribution for Sample Group 12

Table 47 shows the LCA results of Sample Group 12 for Coca-Cola Diet Coke Cans based on each phase. Figures A.56 to A.60 in the Appendix A show the contribution of each phase to each life cycle impact indicator for Sample Group 12.

Table 47 Total life cycle impacts in impact categories of Sample Group 12.

Impact Indicators	Phases	1980	2011
Fossil Fuel Consumption (MJ-equiv)	Manufacture	6,764.10	4,771.80
	Conversion	507.10	357.74
	End of Life	7.36	5.19
Water Consumption (l)	Manufacture	2,349.40	1,657.40
	Conversion	95.50	67.37
	End of Life	2.98	2.10
Biotic Resource Consumption (m^3)	Manufacture	1.10	0.78
	Conversion	0.20	0.14
	End of Life	0.00	0.00
Mineral Consumption (kg)	Manufacture	82.15	57.95
	Conversion	1.22	0.86
	End of Life	0.10	0.07
GHG Emission (kg CO_2-Equiv)	Manufacture	558.48	393.98
	Conversion	37.91	26.74
	End of Life	0.58	0.41

4.3.3 Contribution for Sample Group 13

Table 48 shows the LCA results of Sample Group 13 for Maxwell House Coffee packages based on each phase. Figures A.61 to A.65 in the Appendix A show the contribution of each phase to each life cycle impact indicator for Sample Group 13.

Table 48 Total life cycle impacts in impact categories of Sample Group 13.

Impact Indicators	Phases	1987	2011
Fossil Fuel Consumption (MJ-equiv)	Manufacture	1,695.40	13,556.00
	Conversion	530.88	4,058.30
	End of Life	-14.81	-172.18
Water Consumption (l)	Manufacture	391.62	527.43
	Conversion	108.09	680.97
	End of Life	-1.56	-18.40
Biotic Resource Consumption (m^3)	Manufacture	0.13	0.45
	Conversion	0.73	7.35
	End of Life	-0.01	-0.12
Mineral Consumption (kg)	Manufacture	22.59	4.91
	Conversion	4.19	6.42
	End of Life	0.00	0.02
GHG Emission (kg CO^2-Equiv)	Manufacture	61.68	305.67
	Conversion	35.48	268.46
	End of Life	5.68	58.04

4.4 Category 4: Rigid plastic

Figures 70 to 74 show the comparisons of the LCA results between the old package and the current package of the sample groups in Category 4. Figure 70 is for fossil fuel consumption, Figure 71 is for water consumption, Figure 72 is for biotic resource consumption, Figure 73 is for mineral resource consumption, and Figure 74 is for greenhouse gas (GHG) emissions.

For these rigid plastic packages, there is not much difference between the old and current LCA values. This is because in all samples they are the same plastic (PET or PP), and in most cases they are almost the same weight. In cases of Sample Group 14 for Coca-Cola bottles, Sample Group 15 for Kraft Parmesan Cheese bottles, Sample Group 17 for Dannon Plain Yogurt cups, Sample Group 18 for Dannon Yogurt small size cups, Sample Group 19 for Absopure Water bottles, and Sample Group 20 for Hershey's Chocolate Syrup containers, the old packages demand slightly more fossil fuel, water, biotic resources, and mineral resources and generate more GHG than the current packages.

In case of Sample Group 16 for JIF Peanut Butter containers, the old package demanded slightly more fossil fuel, water, and biotic resources and generated more GHG than the current package. The current package demanded slightly more mineral resource than the old package because of bleached paper.

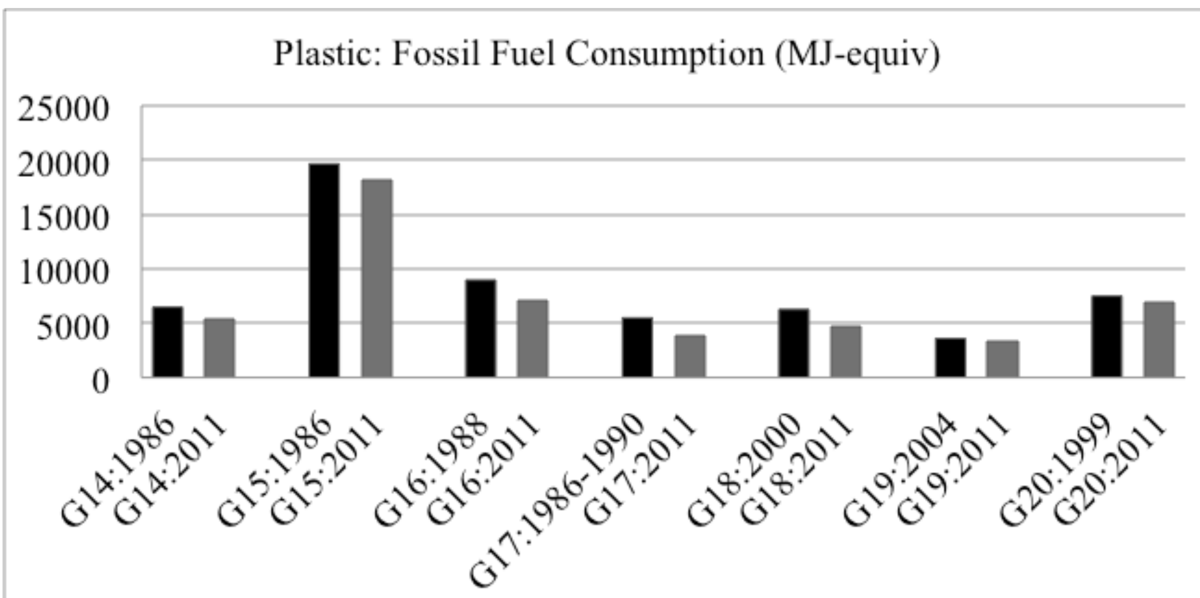

Figure 70 Fossil fuel consumption of Sample Groups in Category 4

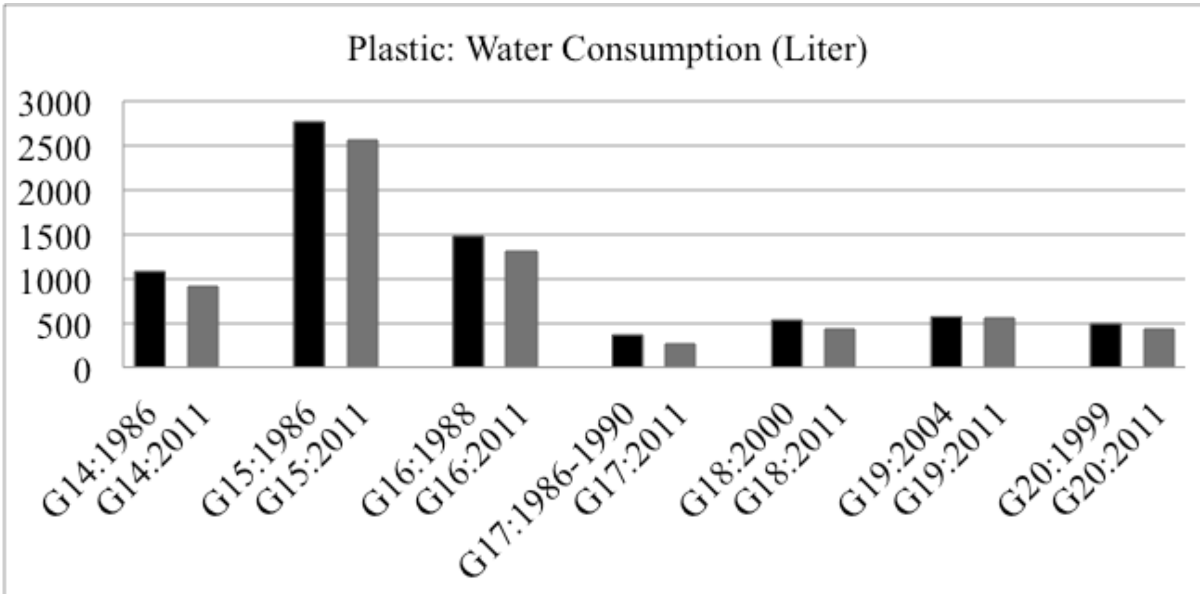

Figure 71 Water consumption of Sample Groups in Category 4

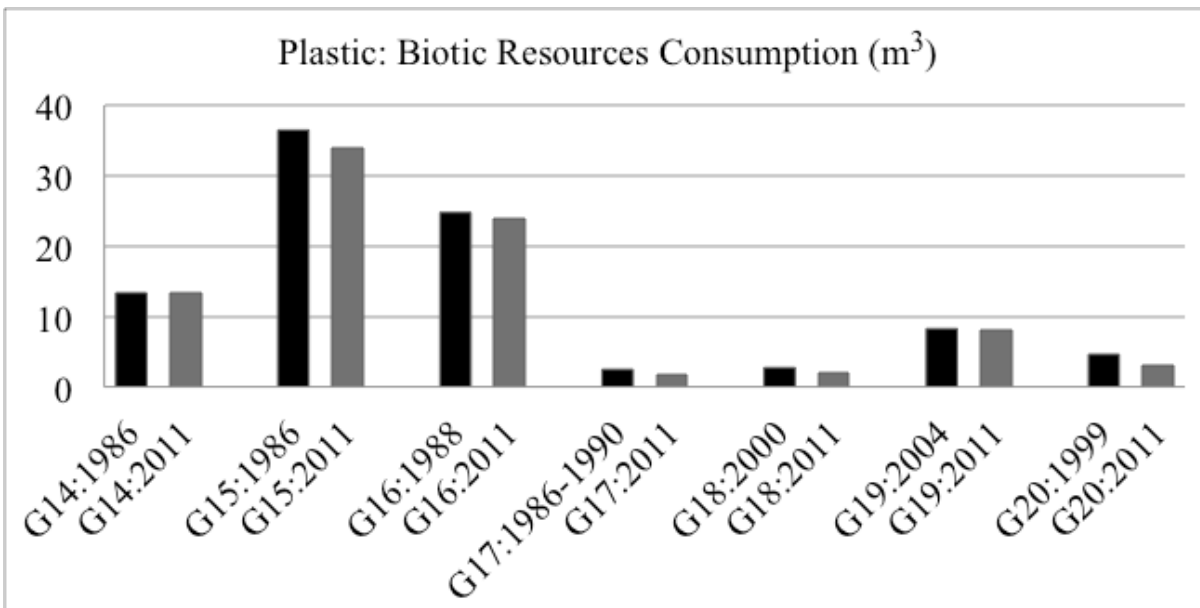

Figure 72 Biotic resources consumption of Sample Groups in Category 4

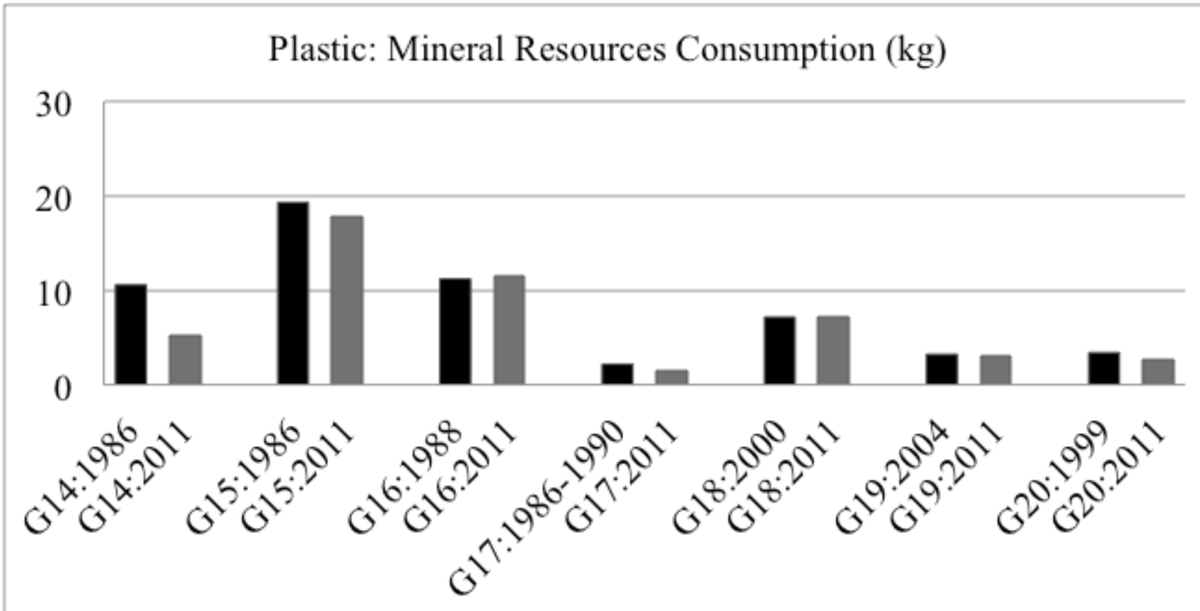

Figure 73 Mineral resources consumption of Sample Groups in Category 4

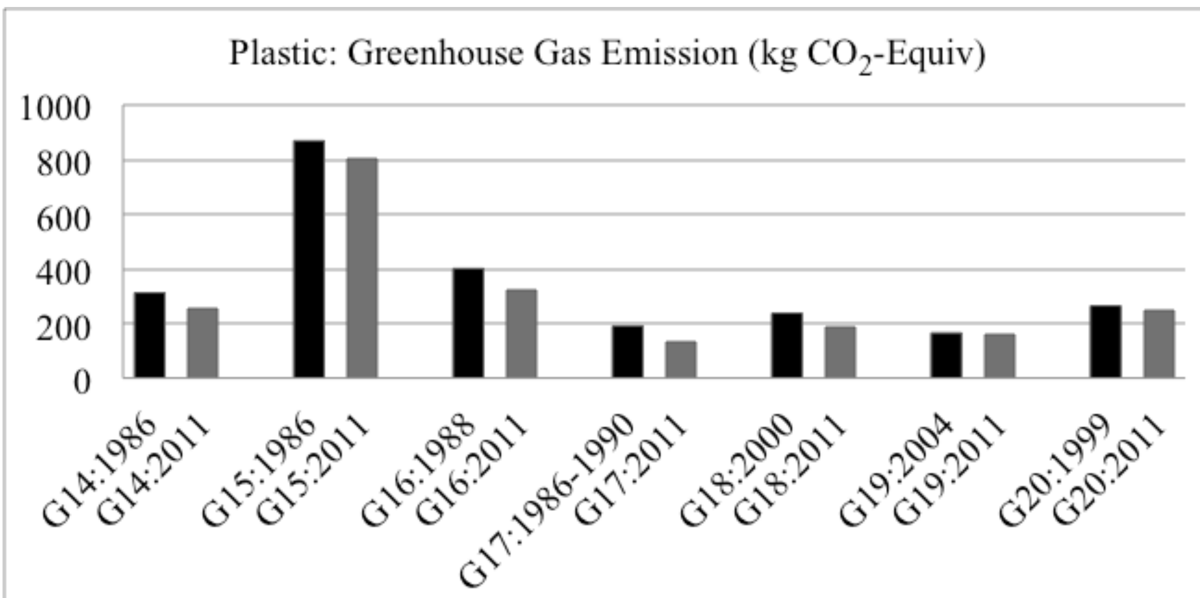

Figure 74 Greenhouse gas emissions of Sample Groups in Category 4

As shown in the following sections, which detail the results from each sample group, manufacturing of the rigid plastic packages was found to be the primary contributor to the consumption of fossil fuel and GHG emissions. This is because of the energy assigned to make, extract and process raw materials and fuel resources such as crude oil and natural gas. The conversion process is a secondary contributor for fossil fuel consumption and GHG emissions, because of the production process of the rigid plastic packages using the resins such as blow molding of bottles and injection molding of caps. Fossil fuel consumption and GHG emissions are closely related in this category, since the majority of the GHG emissions is fossil fuel-related for the flake production and energy used to convert the flake to pellet.

The primary contributor to the water consumption, biotic resource consumption, and mineral resource consumption is the conversion phase for most plastic packages in this study, but the consumption of these resources is small.

The end-of-life phase is a negative source of fossil fuel consumption, water consumption, biotic resource consumption, and mineral resource consumption for both packages since the material can be recycled or recovered from waste to energy, representing a credit of fossil fuel/other resources that can be avoided of resource use. As Table A1 in Appendix B indicates, by using COMPASS, the end-of-life phase of PET beverage bottles composed of 36.6% recycling, 12.6% waste to energy, and 50.8% landfill. The end-of-life of the other PET containers composed of 15.6% recycling, 12.6% waste to energy, and 71.8% landfill.

4.4.1 Contribution for Sample Group 14

Table 49 shows the LCA results of Sample Group 14 for Coca-Cola bottles based on each phase. Figures A.66 to A.70 in the Appendix A show the contribution of each phase to each life cycle impact indicator for Sample Group 14.

Table 49 Total life cycle impacts in impact categories of Sample Group 14.

Impact Indicators	Phases	1986	2011
Fossil Fuel Consumption (MJ-equiv)	Manufacture	5,222.80	4,271.80
	Conversion	1,315.40	1,113.20
	End of Life	-65.75	-60.24
Water Consumption (l)	Manufacture	384.24	219.28
	Conversion	701.72	690.90
	End of Life	-6.62	-6.70
Biotic Resource Consumption (m^3)	Manufacture	0.60	0.53
	Conversion	12.76	12.95
	End of Life	-0.04	-0.04
Mineral Consumption (kg)	Manufacture	5.64	0.41
	Conversion	4.94	4.74
	End of Life	0.00	-0.01
GHG Emission (kg CO_2-Equiv)	Manufacture	208.52	165.90
	Conversion	88.86	75.29
	End of Life	14.22	11.88

4.4.2 Contribution for Sample Group 15

Table 50 shows the LCA results of Sample Group 15 for Kraft Parmesan Cheese bottles based on each phase. Figures A.71 to A.75 in the Appendix A show the contribution of each phase to each life cycle impact indicator for Sample Group 15.

Table 50 Total life cycle impacts in impact categories of Sample Group 15.

Impact Indicators	Phases	1986	2011
Fossil Fuel Consumption (MJ-equiv)	Manufacture	15,729.00	14,453.00
	Conversion	4,169.10	3,823.30
	End of Life	-209.87	-193.00
Water Consumption (l)	Manufacture	832.30	766.99
	Conversion	1,960.50	1,822.20
	End of Life	-22.75	-20.92
Biotic Resource Consumption (m^3)	Manufacture	1.52	1.42
	Conversion	35.12	32.73
	End of Life	-0.14	-0.13
Mineral Consumption (kg)	Manufacture	5.24	4.79
	Conversion	14.06	13.03
	End of Life	-0.02	-0.02
GHG Emission (kg CO_2-Equiv)	Manufacture	539.26	498.78
	Conversion	280.38	257.20
	End of Life	50.12	45.89

4.4.3 Contribution for Sample Group 16

Table 51 shows the LCA results of Sample Group 16 for JIF Peanut butter containers based on each phase. Figures A.76 to A.80 in the Appendix A show the contribution of each phase to each life cycle impact indicator for Sample Group 16.

Table 51 Total life cycle impacts in impact categories of Sample Group 16.

Impact Indicators	Phases	1988	2011
Fossil Fuel Consumption (MJ-equiv)	Manufacture	7,145.30	5,619.50
	Conversion	1,925.20	1,469.30
	End of Life	-95.97	-73.79
Water Consumption (l)	Manufacture	558.04	572.55
	Conversion	930.29	745.56
	End of Life	-10.19	-7.51
Biotic Resource Consumption (m^3)	Manufacture	8.21	10.43
	Conversion	16.61	13.43
	End of Life	-0.07	-0.05
Mineral Consumption (kg)	Manufacture	4.58	6.27
	Conversion	6.63	5.27
	End of Life	-0.01	0.00
GHG Emission (kg CO_2-Equiv)	Manufacture	245.20	200.99
	Conversion	129.55	99.17
	End of Life	26.49	22.33

4.4.4 Contribution for Sample Group 17

Table 52 shows the LCA results of Sample Group 52 for Dannon Plain Yogurt cups based on each phase. Figures A.81 to A.85 in the Appendix A show the contribution of each phase to each life cycle impact indicator for Sample Group 17.

Table 52 Total life cycle impacts in impact categories of Sample Group 17.

Impact Indicators	Phases	1986-1990	2011
Fossil Fuel Consumption (MJ-equiv)	Manufacture	4,233.30	2,925.40
	Conversion	1,318.90	911.45
	End of Life	-56.23	-38.87
Water Consumption (l)	Manufacture	150.49	104.00
	Conversion	221.12	152.81
	End of Life	-6.22	-4.30
Biotic Resource Consumption (m^3)	Manufacture	0.13	0.09
	Conversion	2.40	1.66
	End of Life	-0.04	-0.03
Mineral Consumption (kg)	Manufacture	0.11	0.08
	Conversion	2.08	1.44
	End of Life	0.00	0.00
GHG Emission (kg CO_2-Equiv)	Manufacture	87.26	60.30
	Conversion	87.17	60.24
	End of Life	16.36	11.30

4.4.5 Contribution for Sample Group 18

Table 53 shows the LCA results of Sample Group 18 for Dannon Yogurt small size cups based on each phase. Figures A.86 to A.90 in the Appendix A show the contribution of each phase to each life cycle impact indicator for Sample Group 18.

Table 53 Total life cycle impacts in impact categories of Sample Group 18.

Impact Indicators	Phases	2000	2011
Fossil Fuel Consumption (MJ-equiv)	Manufacture	4,896.40	3,662.90
	Conversion	1,432.60	1,034.90
	End of Life	-58.74	-41.43
Water Consumption (l)	Manufacture	296.52	270.37
	Conversion	240.79	174.20
	End of Life	-5.87	-3.87
Biotic Resource Consumption (m^3)	Manufacture	0.20	0.17
	Conversion	2.57	1.84
	End of Life	-0.04	-0.03
Mineral Consumption (kg)	Manufacture	4.89	5.55
	Conversion	2.28	1.66
	End of Life	0.01	0.01
GHG Emission (kg CO_2-Equiv)	Manufacture	125.26	103.35
	Conversion	94.94	68.69
	End of Life	17.46	12.50

4.4.6 Contribution for Sample Group 19

Table 54 shows the LCA results of Sample Group 19 for Absopure Water bottles based on each phase. Figures A.91 to A.95 in the Appendix A show the contribution of each phase to each life cycle impact indicator for Sample Group 19.

Table 54 Total life cycle impacts in impact categories of Sample Group 19.

Impact Indicators	Phases	2004	2011
Fossil Fuel Consumption (MJ-equiv)	Manufacture	2,867.90	2,690.30
	Conversion	756.38	703.22
	End of Life	-40.19	-37.80
Water Consumption (l)	Manufacture	142.54	135.52
	Conversion	430.56	416.40
	End of Life	-4.47	-4.20
Biotic Resource Consumption (m^3)	Manufacture	0.33	0.32
	Conversion	7.97	7.76
	End of Life	-0.03	-0.03
Mineral Consumption (kg)	Manufacture	0.25	0.25
	Conversion	2.99	2.87
	End of Life	-0.01	-0.01
GHG Emission (kg CO_2-Equiv)	Manufacture	105.98	101.51
	Conversion	51.04	47.51
	End of Life	8.30	7.66

4.4.7 Contribution for Sample Group 20

Table 55 shows the LCA results of Sample Group 20 for Hershey's Chocolate Syrup containers based on each phase. Figures A.96 to A.100 in the Appendix A show the contribution of each phase to each life cycle impact indicator for Sample Group 20.

Table 55 Total life cycle impacts in impact categories of Sample Group 20.

Impact Indicators	Phases	1999	2011
Fossil Fuel Consumption (MJ-equiv)	Manufacture	5,804.10	5,394.40
	Conversion	1,765.50	1,644.80
	End of Life	-76.02	-70.73
Water Consumption (l)	Manufacture	202.79	157.57
	Conversion	296.02	275.75
	End of Life	-8.34	-7.80
Biotic Resource Consumption (m^3)	Manufacture	1.47	0.16
	Conversion	3.22	3.00
	End of Life	-0.05	-0.05
Mineral Consumption (kg)	Manufacture	0.63	0.13
	Conversion	2.78	2.59
	End of Life	0.01	0.01
GHG Emission (kg CO_2-Equiv)	Manufacture	120.73	112.54
	Conversion	116.72	108.70
	End of Life	26.79	24.28

4.5 Category 5: McDonald's

Figures 75 to 79 show the comparisons of the LCA results between the old package and the current package of the Sample Groups in Category 4. Figure 75 is for fossil fuel consumption, Figure 76 is for water consumption, Figure 77 is for biotic resource consumption, Figure 78 is for mineral resource consumption, and Figure 79 is for greenhouse gas (GHG) emissions.

In cases of all Sample Groups for McDonald's packages in Category 5, the corrugated paperboard clamshell for the current package demanded more water, biotic resources, and mineral resources and generated slightly more GHG than the EPS clamshell for the old package.

This is because the EPS merely needs resources while the paperboard needs trees harvested to make paperboard, the clay coating, and has high energy and water usage in the pulping process.

However, if paperboard packages do not degrade after disposal, they store carbon and generate less greenhouse gas emissions than EPS packages. They generate higher greenhouse gas emissions than EPS packages, if paperboard packages degrade to the maximum extent (Franklin 2011).

Another important factor for this result is post-consumer recycled (PCR) content of the corrugated paperboard clamshell for the current package. The paperboard clamshell is made of paperboards with 37% PCR. In COMPASS, the higher PCR rate increases the GHG emissions for the manufacturing phase of the corrugated paperboard clamshell.

The higher PCR rate generally reduces GHG emissions for some materials such as polymers, but for paper that is not always the case. According to Minal Mistry of SPC, who is the author of the COMPASS guide manual, it depends very much on how the specific paper is made. For example, in North America integrated mills use waste wood and fibers as a source of fuel to generate the steam used for heating the pulp and drying the paper, thus they have low purchased fuels and electricity from the grid. On the other hand, most recycled paper mills operate using direct grid energy or purchased fuels such as gas and oil for heating. This raises their GHG profile. In Europe, where trees aren't as abundant as in North America, they tend to purchase what is called market pulp, or dried pulp made in the U.S or Canada, which is rehydrated and made into paper using electricity. Each of these processes has a different fuel profile and consequently their GHG burdens vary widely. This is why in the US some virgin papers have a better profile than their PCR counterpart.

Therefore, which product was better when it comes to greenhouse gas emissions depends on the disposal method and condition at the end-of-life stage because of uncertainties over whether paper-based products degrade after disposal.

The EPS clamshell demanded more fossil fuel consumption than the corrugated paperboard clamshell.

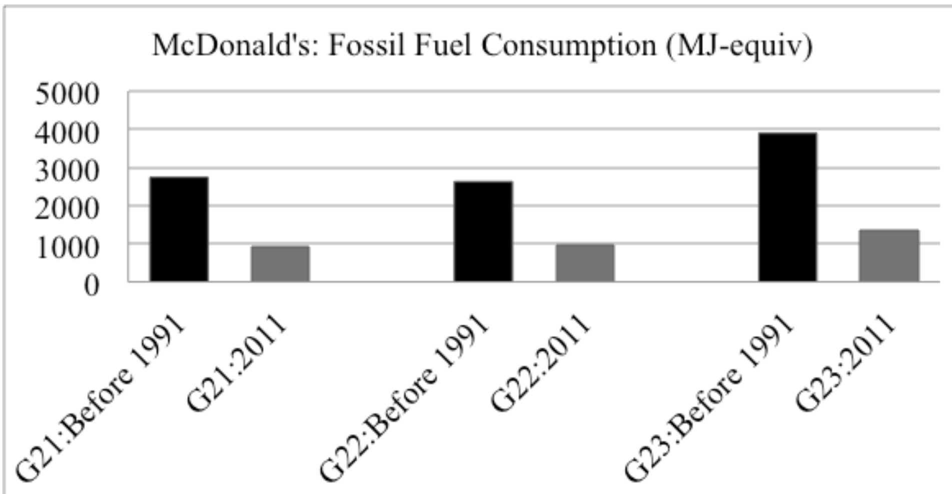

Figure 75 Fossil fuel consumption of Sample Groups in Category 5

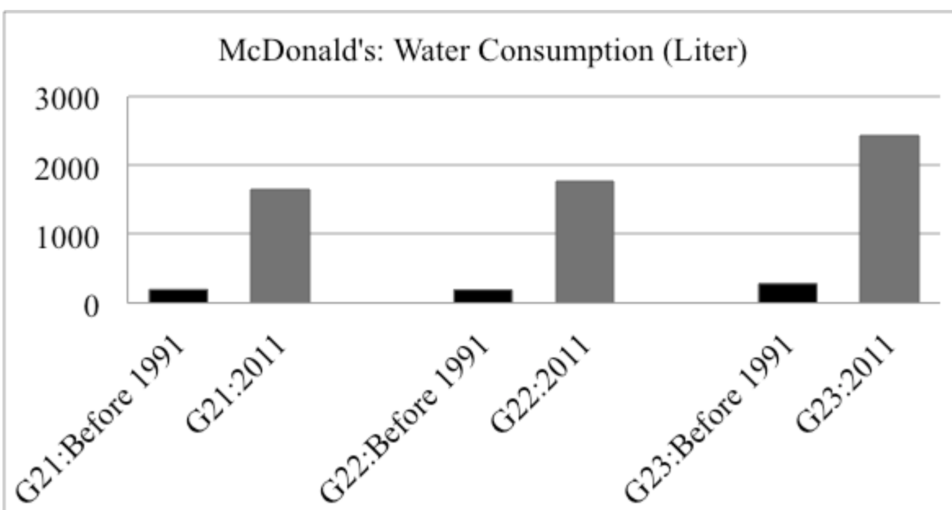

Figure 76 Water consumption of Sample Groups in Category 5

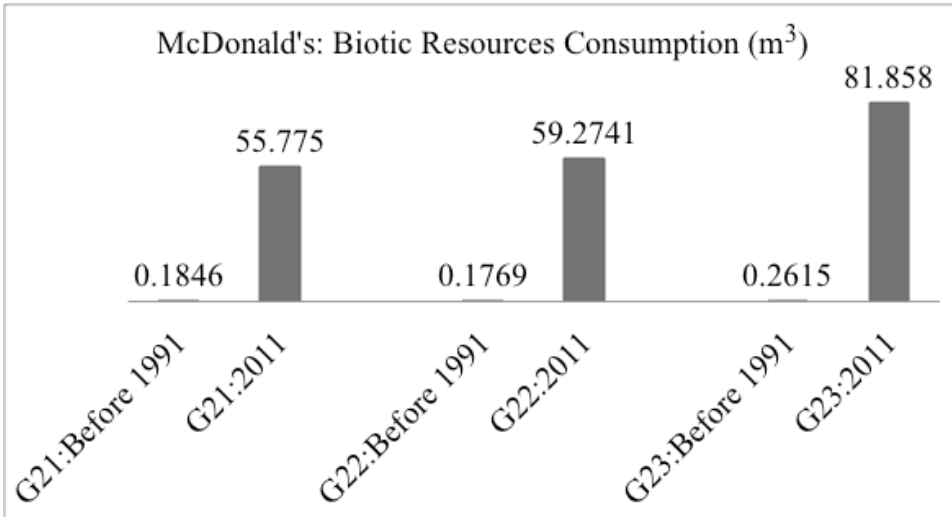

Figure 77 Biotic resource consumption of Sample Groups in Category 5

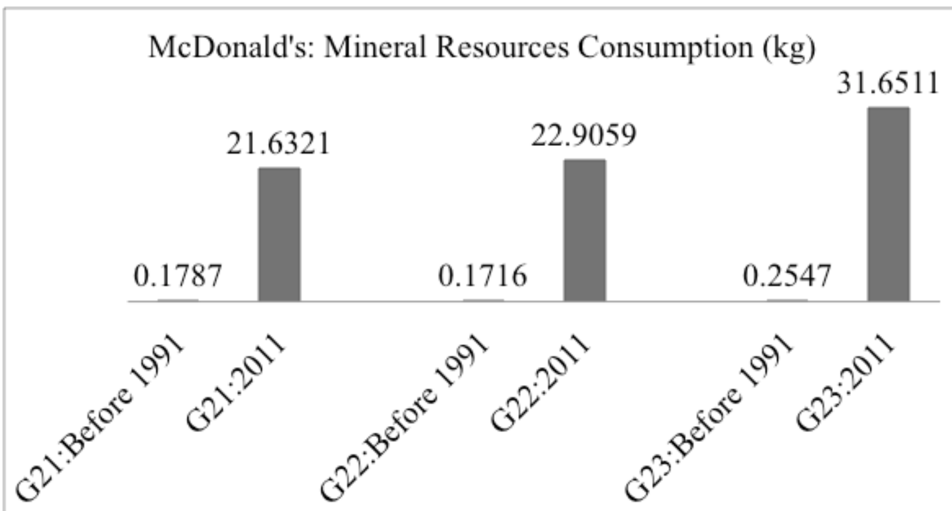

Figure 78 Mineral resource consumption of Sample Groups in Category 5

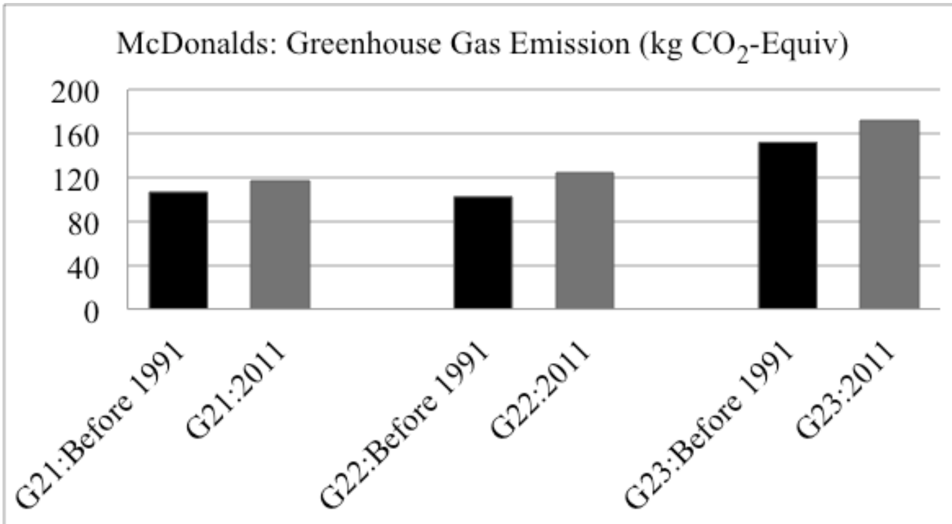

Figure 79 Greenhouse gas emissions of Sample Groups in Category 5

As shown in the following sections, which detail the results from each sample group, manufacturing of the EPS clamshells was found to be the primary contributor to the consumption of fossil fuel, water, mineral and biotic resources, and GHG emissions. This is because there are manufacturing-related GHG emissions from resin production processes such as raw material extraction. The conversion phase is the second highest contributor for EPS clamshells, since it generates GHG from the production and destruction of the blowing agent used in foam product conversion. The end-of-life phase for EPS clamshells has relatively less impact, because they have a high carbon content and do not decompose to produce methane in landfills (Franklin 2011).

The end-of-life phase of the corrugated paperboard clamshells was found to be the main contributor to GHG emissions, since paperboard generates GHG as it decomposes. End-of-life results for paperboard products vary considerably depending on assumptions about decomposition, as discussed at Category 1 of this Chapter. The manufacturing phase of the corrugated paperboard clamshells is the second highest contributor to the GHG emissions.

The manufacturing phase of the paperboard was found to be the primary contributor to the consumption of fossil fuel, water, mineral and biotic resources. This is because of the trees harvested to make paperboard, the clay coating, and the high energy and water usage in the pulping process, including the repulping process for recycled paperboard. The conversion process is a secondary contributor to resource consumption because the scoring, cutting and corrugating are more mechanical than resource-intensive.

4.5.1 Contribution for Sample Group 21

Table 56 shows the LCA results of Sample Group 21 for McDonald's Big Mac packages based on each phase. Figures A.101 to A.105 in the Appendix A show the contribution of each phase to each life cycle impact indicator for Sample Group 21.

Table 56 Total life cycle impacts in impact categories of Sample Group 21.

Impact Indicators	Phases	Before 1991	2011
Fossil Fuel Consumption (MJ-equiv)	Manufacture	2,486.00	784.61
	Conversion	276.52	165.47
	End of Life	-26.04	-19.58
Water Consumption (l)	Manufacture	134.12	1,539.10
	Conversion	64.84	116.92
	End of Life	-2.86	2.35
Biotic Resource Consumption (m^3)	Manufacture	0.08	52.63
	Conversion	0.12	3.19
	End of Life	-0.02	-0.01
Mineral Consumption (kg)	Manufacture	0.07	20.27
	Conversion	0.09	1.27
	End of Life	0.01	0.06
GHG Emission (kg CO_2-Equiv)	Manufacture	74.16	17.68
	Conversion	22.15	10.04
	End of Life	10.07	89.54

4.5.2 Contribution for Sample Group 22

Table 57 shows the LCA results of Sample Group 22 for McDonald's Quarter Pounder packages based on each phase. Figures A.106 to A.110 in the Appendix A show the contribution of each phase to each life cycle impact indicator for Sample Group 22.

Table 57 Total life cycle impacts in impact categories of Sample Group 22.

Impact Indicators	Phases	Before 1991	2011
Fossil Fuel Consumption (MJ-equiv)	Manufacture	2,388.30	833.26
	Conversion	265.66	175.73
	End of Life	-25.01	-20.79
Water Consumption (l)	Manufacture	128.85	1,634.50
	Conversion	62.30	124.17
	End of Life	-2.75	2.49
Biotic Resource Consumption (m^3)	Manufacture	0.08	55.89
	Conversion	0.11	3.39
	End of Life	-0.02	-0.02
Mineral Consumption (kg)	Manufacture	0.07	21.53
	Conversion	0.09	1.34
	End of Life	0.01	0.07
GHG Emission (kg CO_2-Equiv)	Manufacture	71.25	18.78
	Conversion	21.28	10.66
	End of Life	9.68	95.09

4.5.3 Contribution for Sample Group 23

Table 58 shows the LCA results of Sample Group 23 for McDonald's Filet-O-Fish packages based on each phase. Figures A.110 to A.115 in the Appendix A show the contribution of each phase to each life cycle impact indicator for Sample Group 23.

Table 58 Total life cycle impacts in impact categories of Sample Group 23.

Impact Indicators	Phases	Before 1991	2011
Fossil Fuel Consumption (MJ-equiv)	Manufacture	3,538.30	1,151.60
	Conversion	393.58	242.87
	End of Life	-37.06	-28.74
Water Consumption (l)	Manufacture	190.90	2,258.90
	Conversion	92.29	171.61
	End of Life	-4.07	3.45
Biotic Resource Consumption (m^3)	Manufacture	0.12	77.25
	Conversion	0.17	4.68
	End of Life	-0.03	-0.02
Mineral Consumption (kg)	Manufacture	0.10	29.75
	Conversion	0.13	1.86
	End of Life	0.02	0.09
GHG Emission (kg CO_2-Equiv)	Manufacture	105.55	25.95
	Conversion	31.53	14.74
	End of Life	14.34	131.42

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

The evaluation of environmentally sustainable packaging allows several conclusions to be made when LCA is performed. This is because LCA practitioners set or weight certain impact indicators for their own purposes. For example, if someone wants a packaging design that generates less greenhouse gas, other indicators may not be considered significant even if an alternative packaging demanded much less water and mineral resource consumption.

In this study, the main standard of judgment for whether the current package is more environmentally sustainable than the old package is based on the results of five life cycle impact indicators. Since there was no particular indicator given a higher weight in these five life cycle impact indicators, the final decision which package is more environmentally sustainable in a sample group is made considering all impact indicators. For example, when an old package demands more water resources, biotic resources, and mineral resources than a current package, and the current package generates more GHG emissions and demands more fossil fuel than the old package, the current package is regarded as the more environmentally sustainable than the old package. This is because the current package has less environmental impacts than the old package in three of the five impact indicators.

For paperboard cartons in this study, the manufacturing phase was generally the main contributor for the fossil fuel consumption, water consumption, biotic resource consumption, and mineral consumption.

For glass bottles and jars in this study, the manufacturing phase was the primary contributor for all impact indicators.

For aluminum cans and steel cans, the manufacturing phase was the highest contributor for all impact indicators. The main contributor to the biotic resource consumption for the steel can was the conversion phase, but it was negligible.

For rigid plastic containers, such as PET, PP, HDPE and EPS, the manufacturing phase was generally the highest contributor for fossil fuel consumption and GHG emissions. The main contributor to water consumption, biotic resource consumption, and mineral consumption for the rigid plastic containers was generally the conversion phase.

In case of Category 1 for the four paperboard carton sample groups, the old packages of three sample groups demanded more fossil fuel, water, biotic resources, and mineral resources and generated more GHG than the current packages. The primary reason for these results is the lighter weight of the current packages' paperboard, since the materials of both packages were almost the same. The results mean that the current package has less environmental impacts than the old package for four groups of the five based on the five impact indicators.

Among the six groups of glass bottles and jars for Category 2, two sample groups, Sample Groups 5 and 8, had the same materials between the old package and the current package. Because of their heavier weights, the old packages of these two groups demanded more fossil fuel, water, biotic resources, and mineral resources and generated more GHG emissions. This means that the current package has less environmental impacts than the old package for the two sample groups, since all impact indicators show that result.

In the case of the other four groups for Category 2, the old glass bottles and jars were changed to other materials: a steel can, a PET container, and a paperboard carton.

When the glass jar was changed to a steel can like Sample Group 6, the old glass jar demanded more fossil fuel, water, biotic resources, and mineral resources and generated more

GHG emissions than the current steel can. This means that the can has less environmental impacts, since all impact indicators show this result.

When the glass jar was changed to a PET container, as in Sample Groups 7 and 9, the old glass jars demanded more water, biotic resources, and mineral resources and more or almost same GHG emissions than the current PET containers. This means that the current package has less environmental impacts, since three to four of the five impact indicators show this result.

If the glass jar was changed to a paperboard carton like Sample Group 10, the old glass jar demanded more fossil fuel, water, and mineral resources and generated more GHG than the current paperboard carton. This means that the current package has less environmental impacts than the old package since four of the five impact indicators show this result.

Among three groups of the metal can for Category 3, Sample Group 11 and Sample Group 12, had the same materials between the old package and the current package. The old packages of the sample groups consumed more fossil fuel, water, biotic resources, and mineral resources and generated more GHG than the current packages of the sample groups, because of the lighter weights of the aluminum cans. This means that the current package has less environmental impacts than the old package, since all impact indicators show this result.

Like Sample Group 13, when the steel can for the old package was changed to the HDPE jar for the current package, the current HDPE jar consumed more fossil fuel, water, and biotic resources and generated more GHG emissions than the old steel can. This means that the old package had less environmental impact than the current package, since four of the five impact indicators show this result.

In cases of the seven sample groups in Category 4, the old rigid plastic package consumed more fossil fuel, water, biotic resources, and mineral resources and generated more

GHG than the current rigid plastic package for all sample groups. The main reason for these results is the lighter weight of the current packages' plastic material, since the materials of both packages were not largely changed over time. This means that the current package has less environmental impact than the old package, since all impact indicators show this result.

In case of the three sample groups in Category 5, the EPS clamshell for the old package had less environmental impact than the corrugated paperboard clamshell, because four of the five impact indicators, water consumption, biotic resource consumption, mineral resource consumption, and GHG emissions, increased.

Of the twenty-three comparison sample groups, eighteen groups, 78.3% of the total groups, show that currently produced packages in 2011 had less environmental impact than the old packages from the 1970s to 2000s, through their entire life cycle.

With these results, the hypothesis of this study that most companies in the U.S. have made efforts to design more environmentally sustainably packaging is supported. The reasons for this change include increasing social concerns, such as consumers' needs and government policies. Another reason is the packaging industry's natural tendency to lightweight and to switch to lower cost packaging substitutes (for example from glass) when new technology becomes available. Since the concerns are still increasing around the world, it is expected that this trend will continue in the future.

Due to the limited variety of manufacturing years and sample types in this study, the comparison results between old and current package design may not perfectly represent the absolute trend in all decades. Despite this limitation, the results of LCA using randomly selected samples in this study show a clear trend over time.

5.1 Limitations

A number of assumptions and limitations apply to this study, because life cycle inventory data for some processes in the life cycle of package were simulated, instead of acquiring the actual data. Furthermore, comparative LCA analysis has limitations. It is simple but may easily induce claims without a proper analysis of the robustness of the claims with respect to uncertainties (Heijungs et al. 2008). A number of limitations and uncertainties can be listed:

- The life cycle assessment was performed with the U.S inventory dataset of COMPASS software developed by SPC. Since the database was established by using average values in industry, the inventory data used in this study could be different with actual data values of each company or process.
- This study only used the five impact indicators: GHG emissions, fossil fuel consumption, water consumption, biotic resource consumption, and mineral resource consumption. If other impact indicators are added, the decision of which one has less environmental impacts may change.
- This study considered the results of the five impact indicators equally. If particular impact indicators were weighted as more important factors, the final decision of which one was more environmentally sustainable could change.
- Secondary packaging and packaging systems were excluded from the scope and boundaries of this study. But, it would not be surprising to find that the shipping containers are much more sustainable now that there is more recycled content and lower basis weight board, compared to the 1970s.
- Simple weight measurements do not reflect technology changes over time which may have increased sustainability, as cleaner production.

- For plastic packaging, the difference between conversion and manufacturing phases is not always clear; for example thermoforming may include sheet production as part of manufacturing or conversion.
- The transportation stage was not included in this study.
- Printing processes were excluded because there is no printing section in COMPASS.
- Because the source of old packaging samples was the Museum of Michigan State University, and there were limited numbers of old packaging samples, only one sample could be investigated for each package.
- The packaging samples were manually weighed which could be a source of error.
- Because of the limited number of the old packages, statistical analysis was not performed. For example, t-tests and ANOVA require at least three samples for each product.
- The post-consumer recycling (PCR) rates of packaging materials were entered following the scope of COMPASS software in this study. However, "Due to technology limitations some materials have a cap on the amount of PCR they contain, for example, steel at 35% PCR" (Mistry 2010b, p. 5). If the PCR rate of a material was out of the scope, PCR rates of the materials of the package and alternative were excluded. Since COMPASS could not deal the PCR rate for some of packaging materials, especially plastics, the LCA result for the packages is possible to be changed when the post-consumer recycling (PCR) rate is included into COMPASS.
- There was no historical progression of packages, simply "old" and "new".
- A sensitivity and uncertainty analysis were not included in this study.

- If a component of an old packaging sample was missed, the corresponding component of a current packaging sample was not investigated.

The assumptions in this study include:

- Paper labels of packages were made of bleached paper (BP).
- Plastic labels of packages were made of polypropylene (PP).
- "Because composite components are presumed to require disassembly or processing in order to recover the original materials in the component, composite components are assumed to be non-recyclable in the current recycling system" (Mistry 2010b, p. 5).

5.2 Recommendations for future study

The following elements are recommended:

1. Inventory of LCA extracted from actual processing data will allow for more realistic results.
2. Supply chains and transportation phases need to be included in an LCA.
3. Secondary packaging, cube efficiency, and packaging systems need to be considered in an LCA in order to achieve more holistic results.
4. Investigation of the end-of-life phase for composite components needs to be performed by specific disposal methods. In this study, COMPASS assumed composite components to be non-recyclable.
5. Uncertainty analysis or sensitivity analysis may help with the accuracy of LCA results.
6. Weights of packaging need to be measured more times with more samples for more accurate results.

7. The post-consumer recycling rate of packages should be specifically considered in the LCA software.
8. If an LCA considers specific geographical factors for each product, more accurate results can be obtained. This study used only the U.S average dataset provided by COMPASS.
9. A greater variety of old packaging samples needs to be considered for evaluation so that the conclusions of this study can be validated with more accurate results.
10. Further study of environmental sustainability of packaging connected to economic feasibility of the packaging system is needed.

APPENDICES

APPENDIX A

Figures of the LCA results for each Sample Group

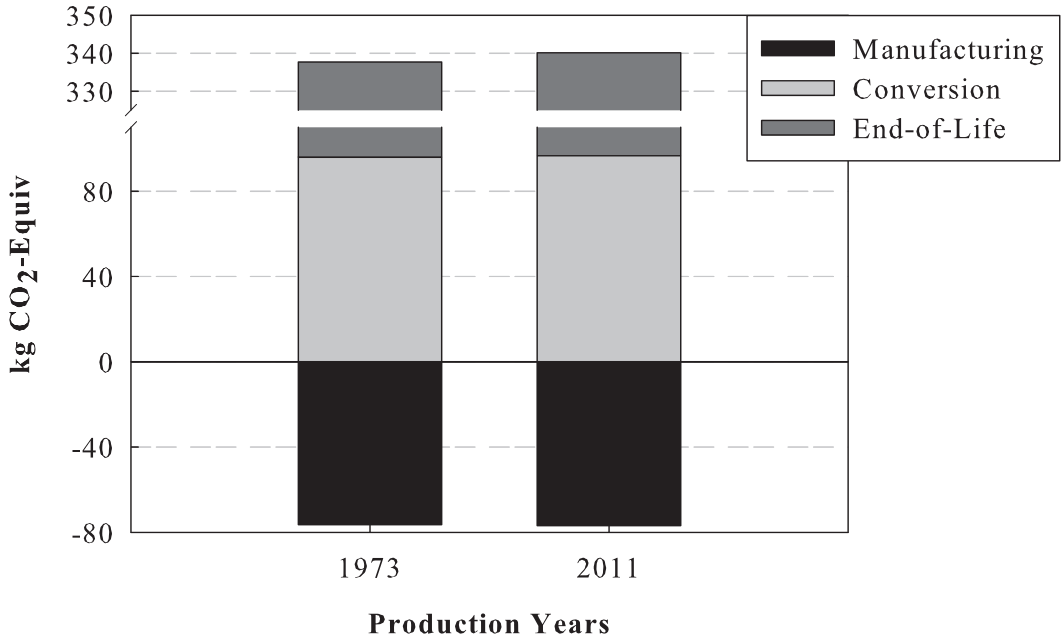

Figure A 1 Global warming potential (in kg CO_2-equiv) of Sample Group 1

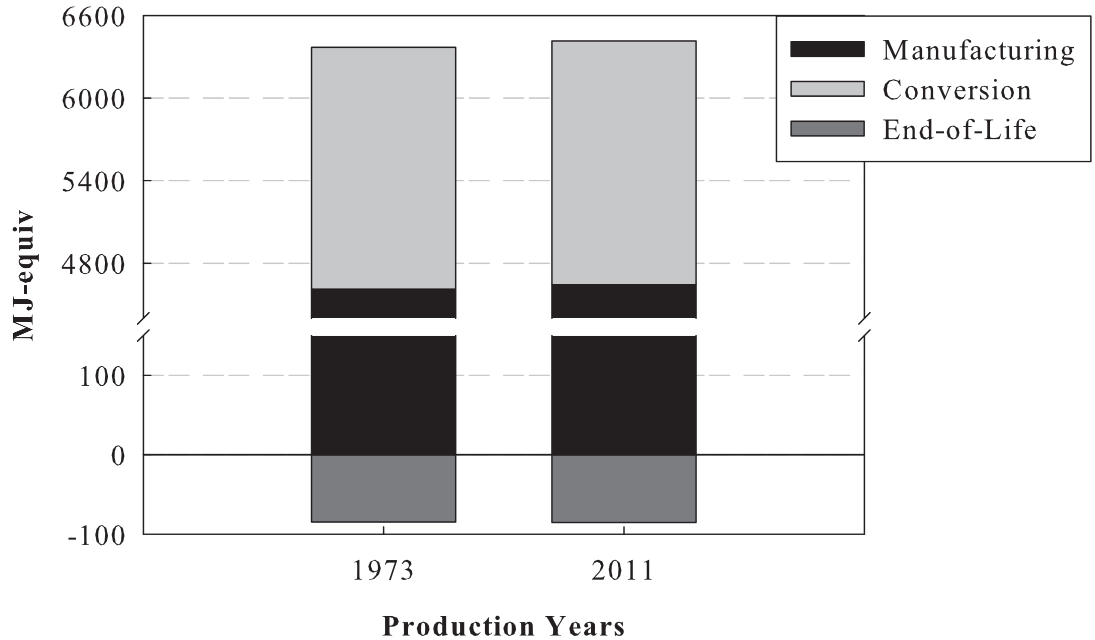

Figure A 2 Fossil fuel consumption (in MJ-equiv) of Sample Group 1

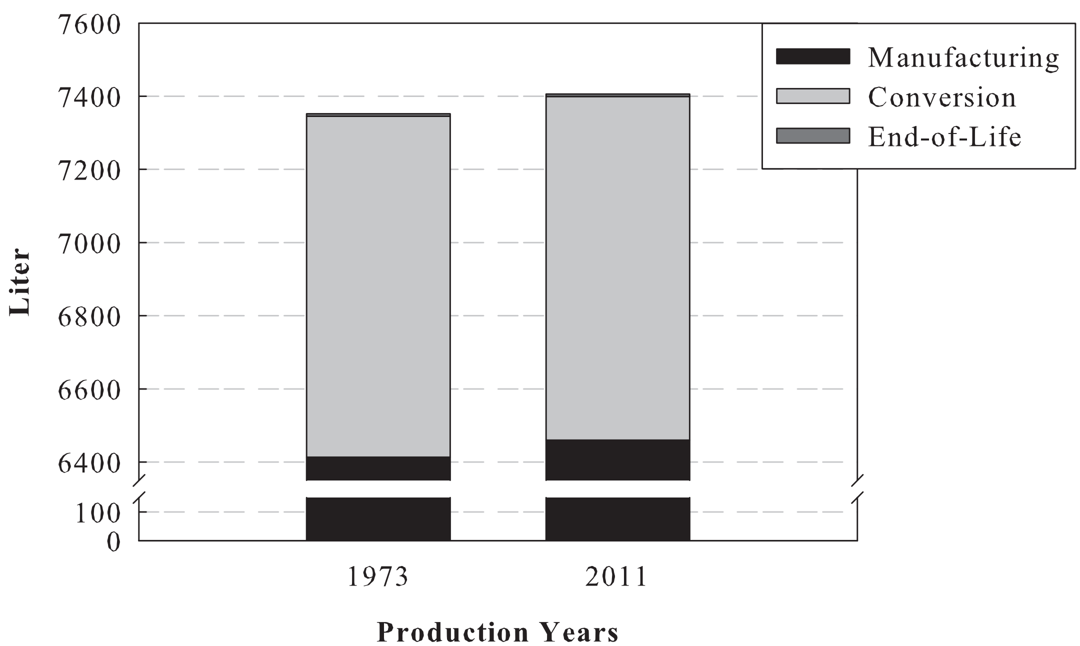

Figure A 3 Water consumption (in liter) of Sample Group 1

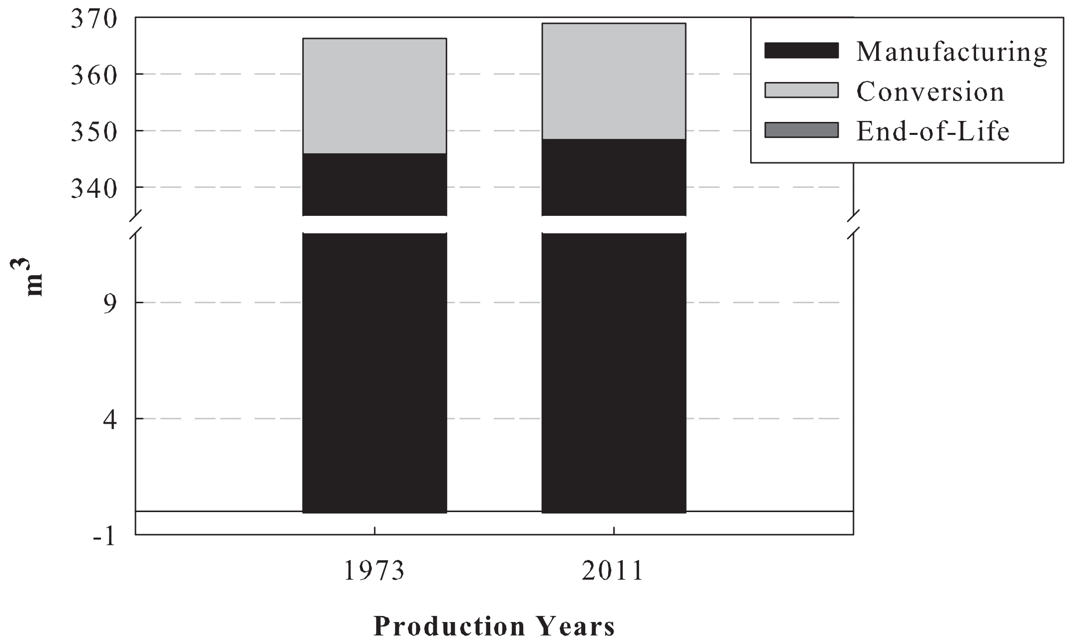

Figure A 4 Biotic resource consumption (in m^3) of Sample Group 1

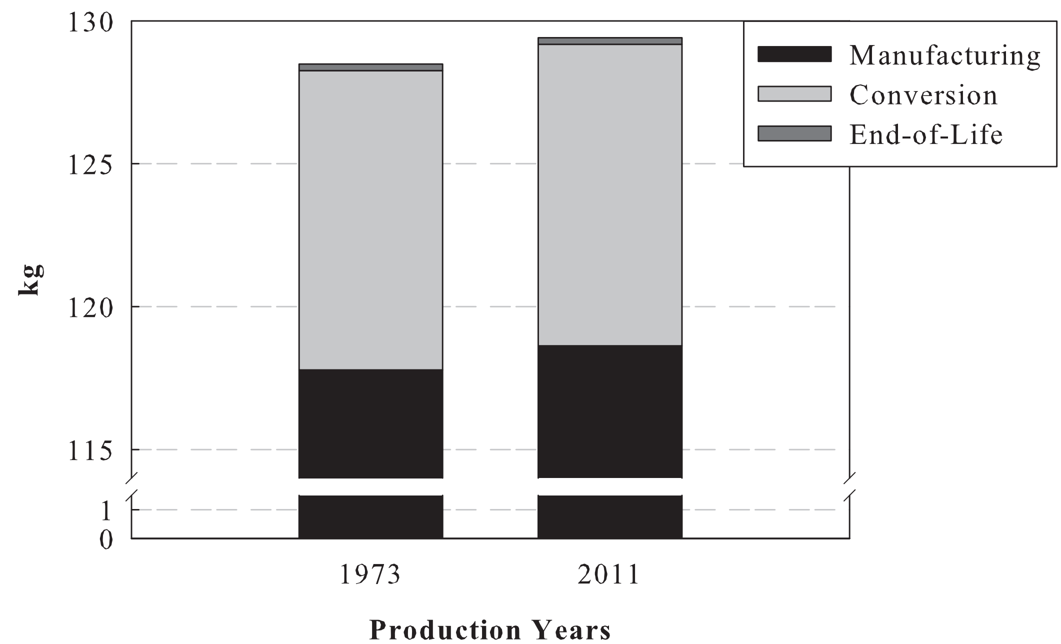

Figure A 5 Mineral resource consumption (in kg) of Sample Group 1

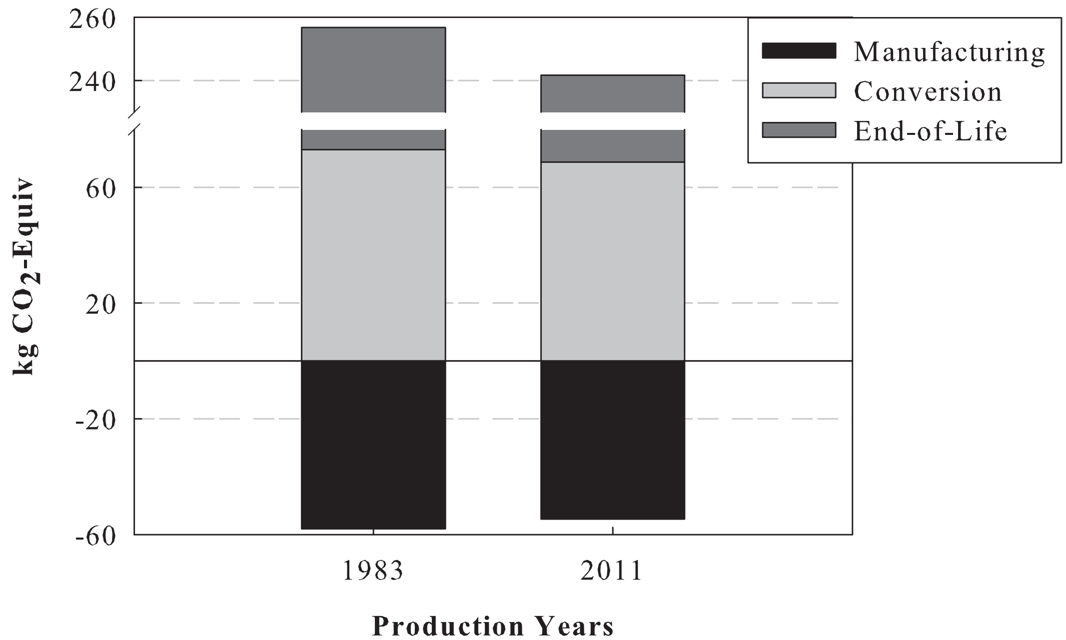

Figure A 6 Global warming potential (in kg CO_2-equiv) of Sample Group 2

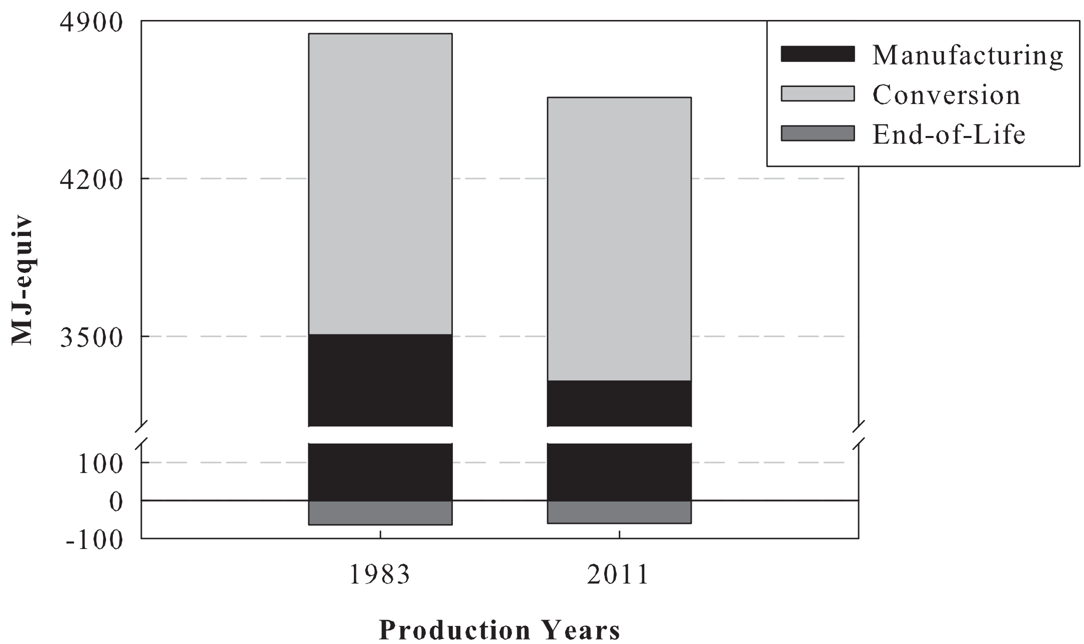

Figure A 7 Fossil fuel consumption (in MJ-equiv) of Sample Group 2

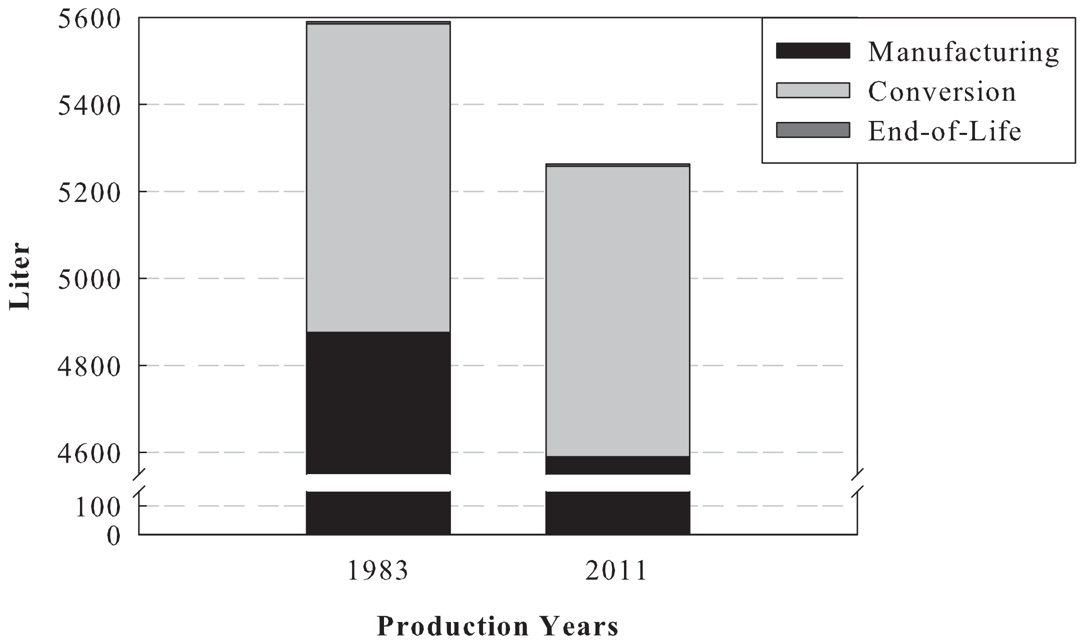

Figure A 8 Water consumption (in liter) of Sample Group 2

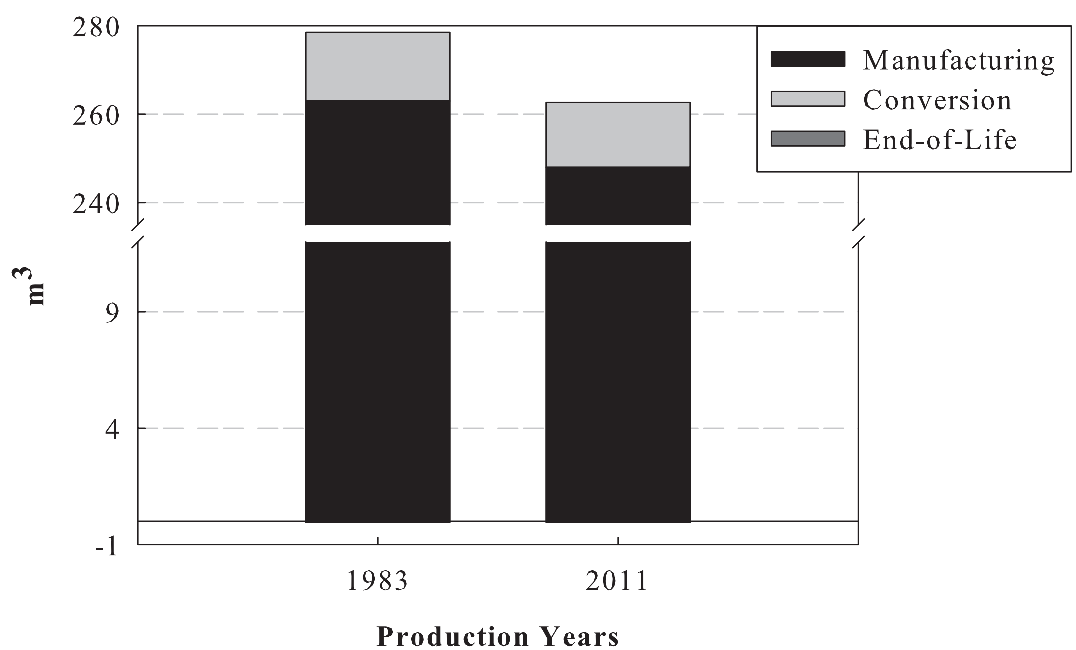

Figure A 9 Biotic resource consumption (in m^3) of Sample Group 2

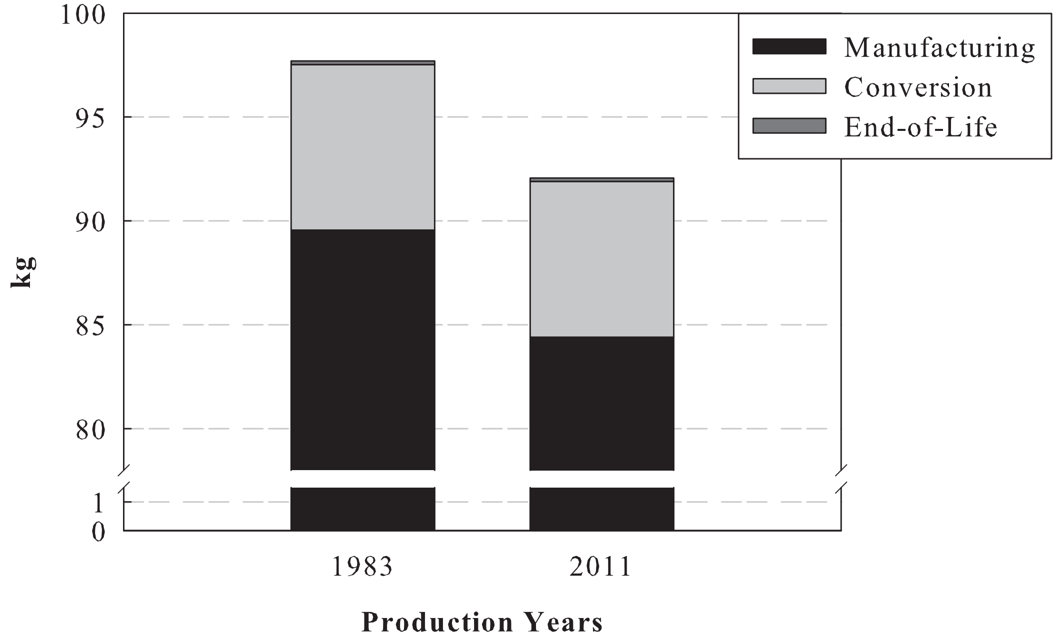

Figure A 10 Mineral resource consumption (in kg) of Sample Group 2

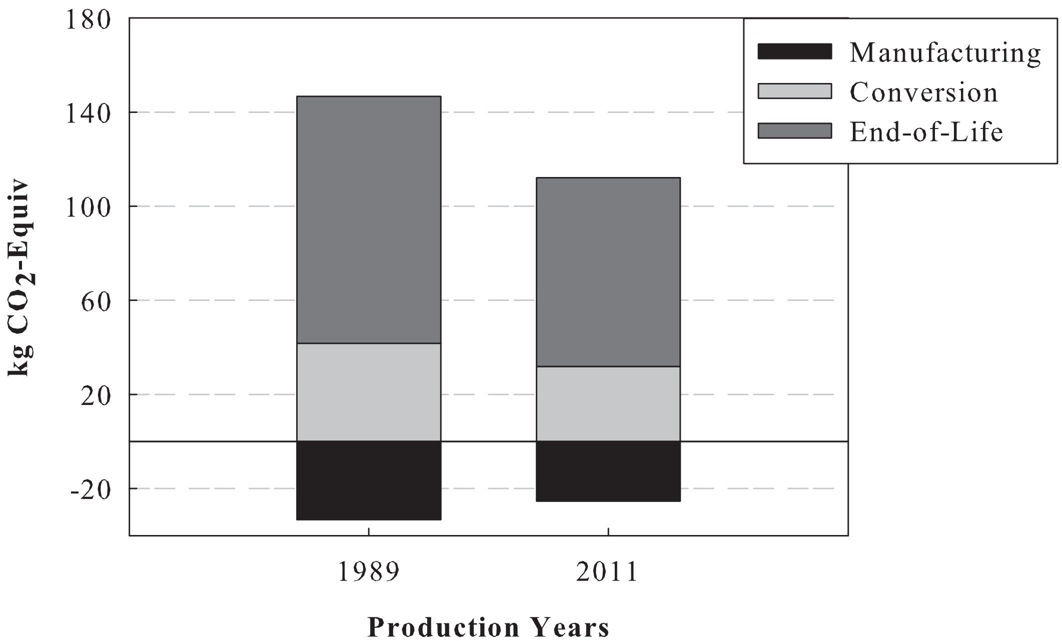

Figure A 11 Global warming potential (in kg CO_2-equiv) of Sample Group 3

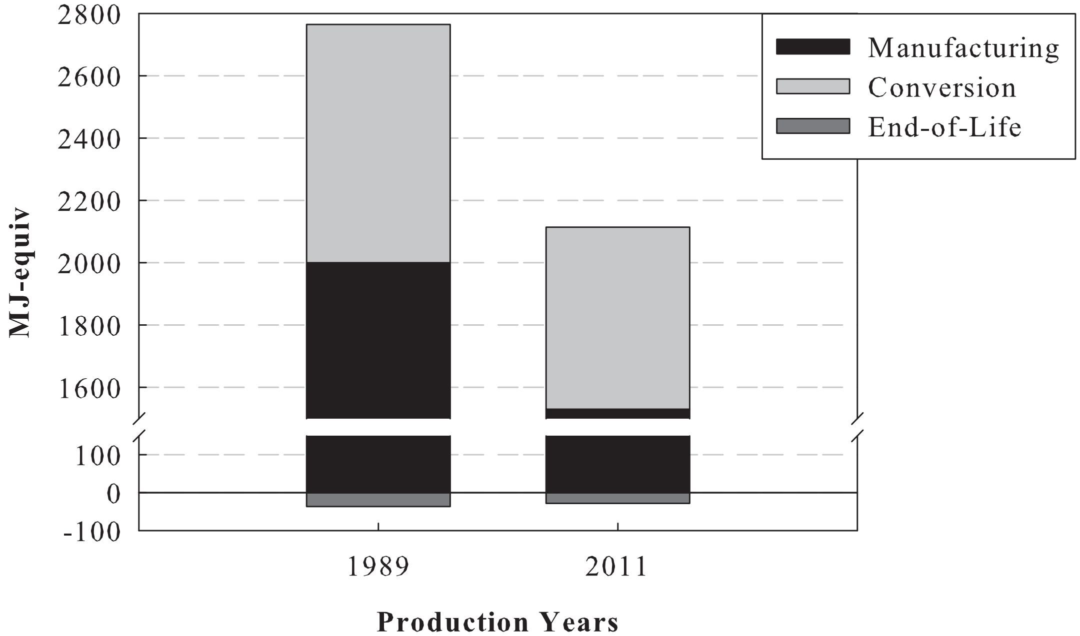

Figure A 12 Fossil fuel consumption (in MJ-equiv) of Sample Group 3

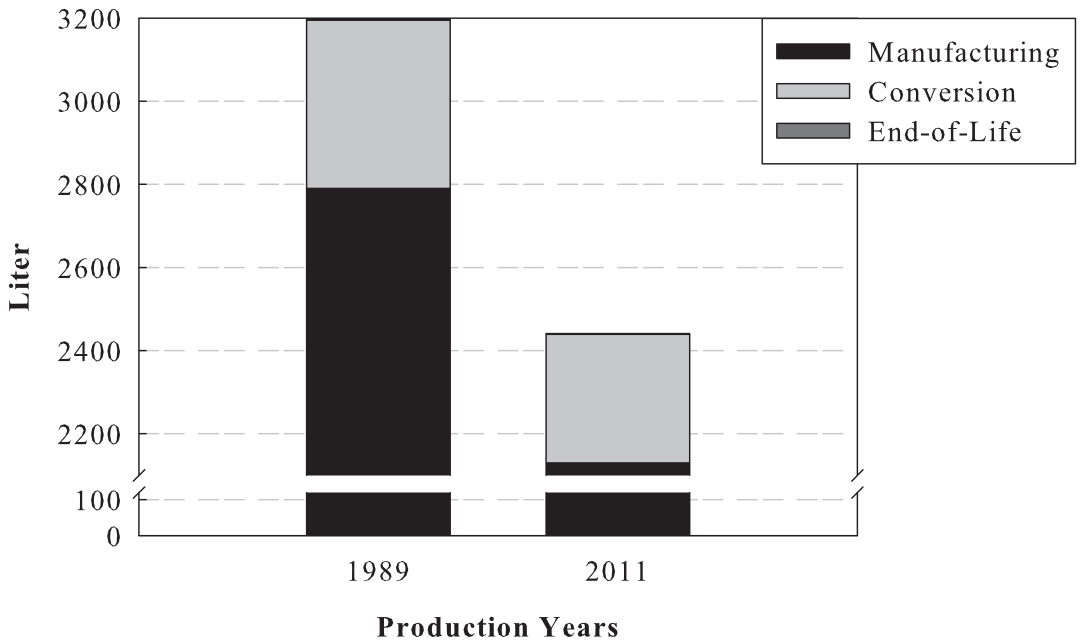

Figure A 13 Water consumption (in liter) of Sample Group 3

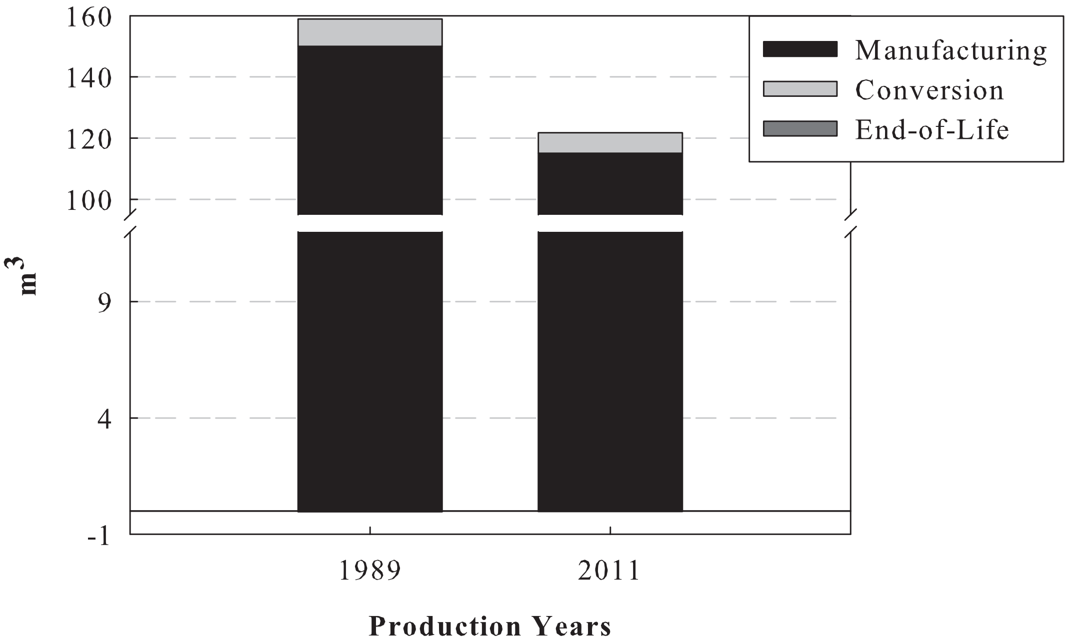

Figure A 14 Biotic resource consumption (in m^3) of Sample Group 3

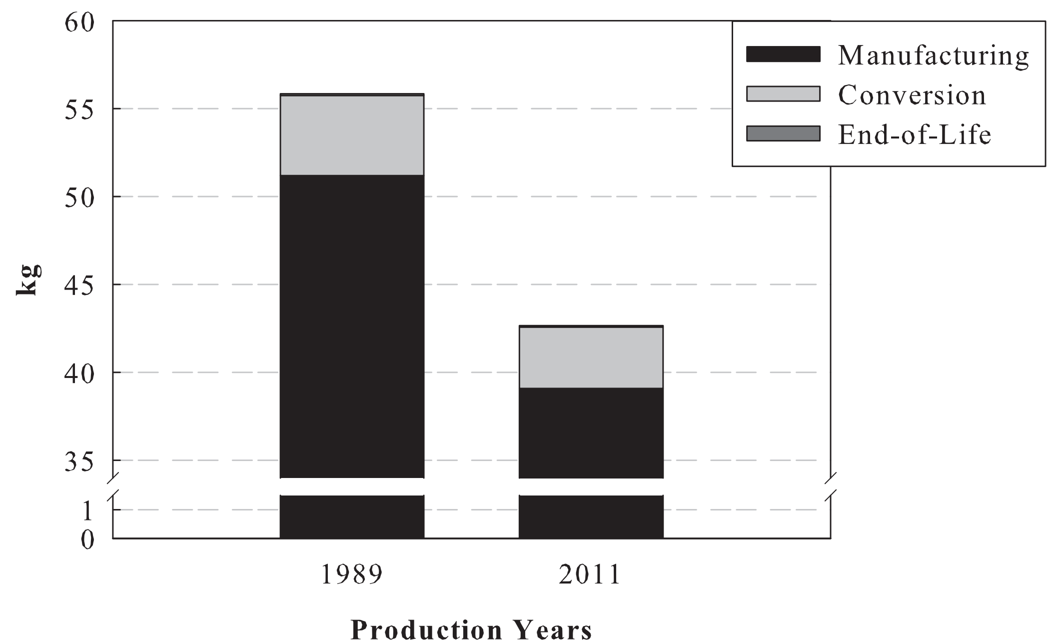

Figure A 15 Mineral resource consumption (in kg) of Sample Group 3

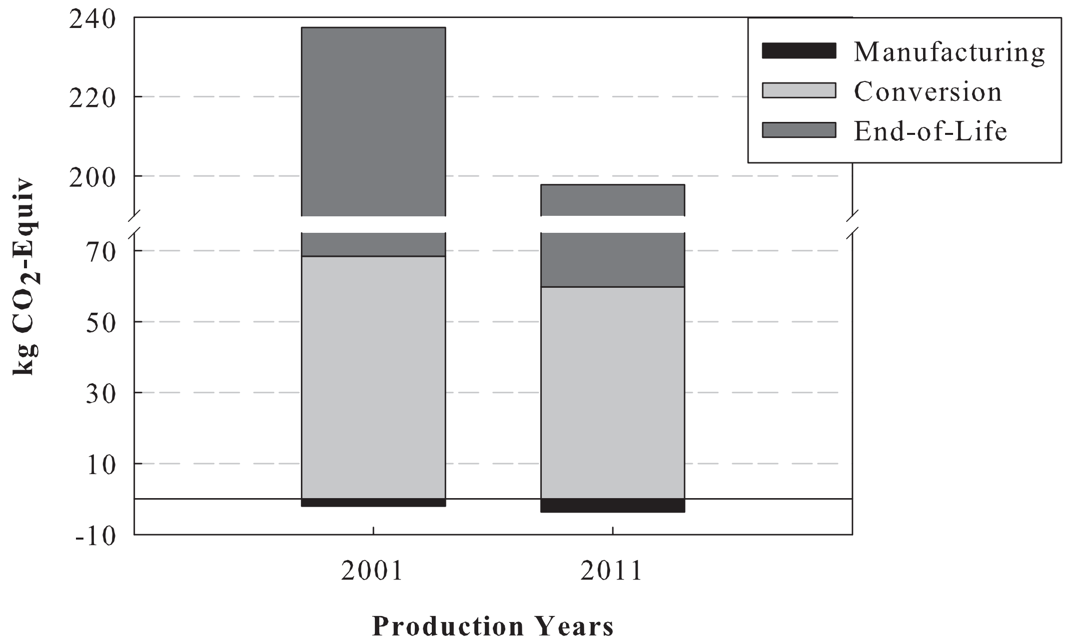

Figure A 16 Global warming potential (in kg CO_2-equiv) of Sample Group 4

Figure A 17 Fossil fuel consumption (in MJ-equiv) of Sample Group 4

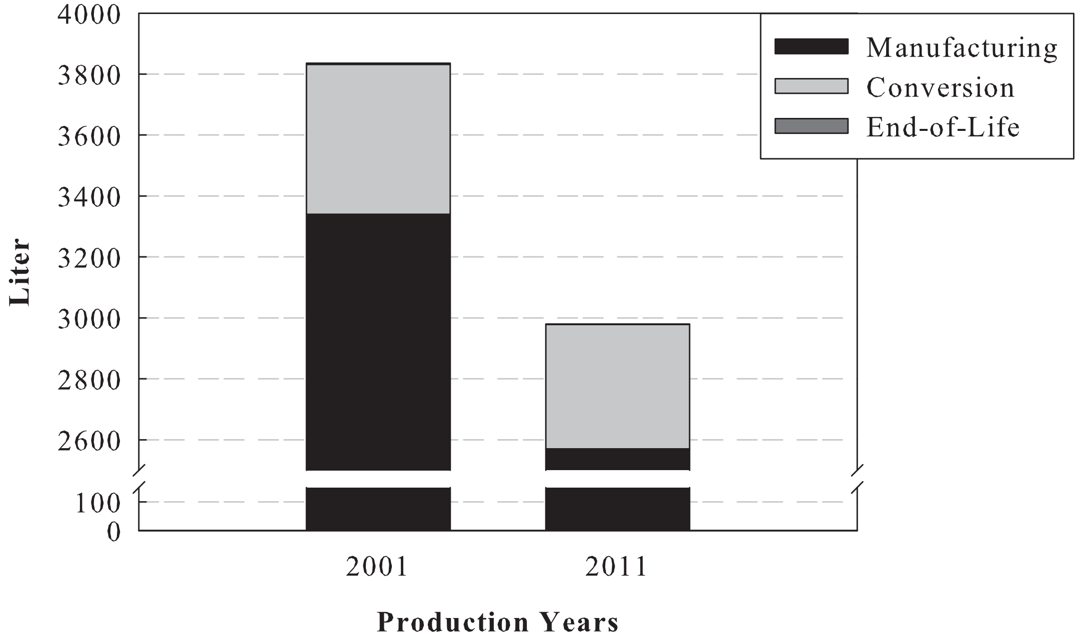

Figure A 18 Water consumption (in liter) of Sample Group 4

Figure A 19 Biotic resource consumption (in m^3) of Sample Group 4

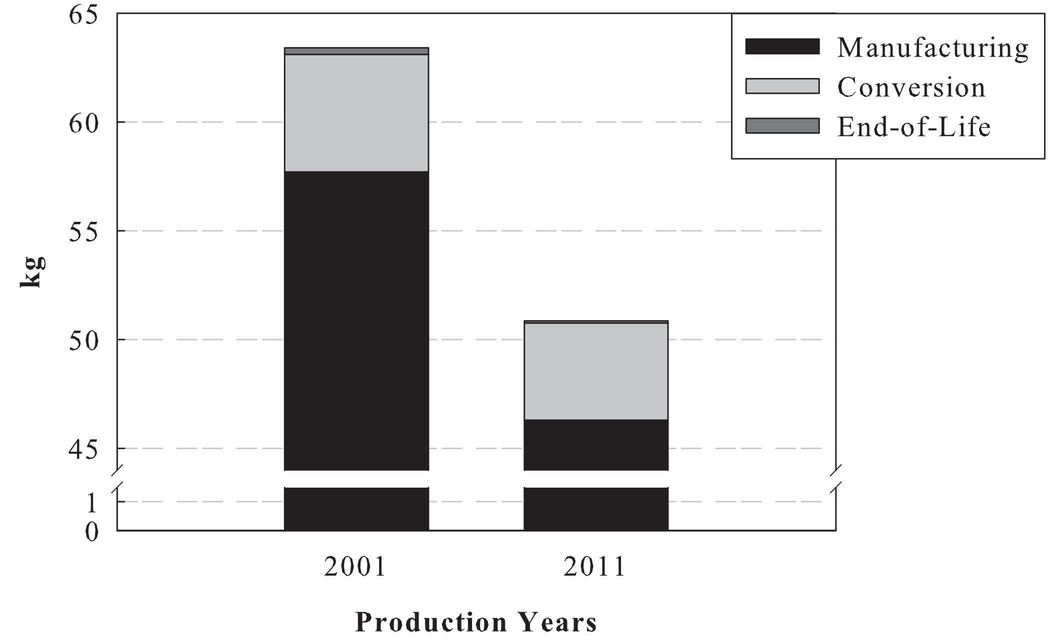

Figure A 20 Mineral resource consumption (in kg) of Sample Group 4

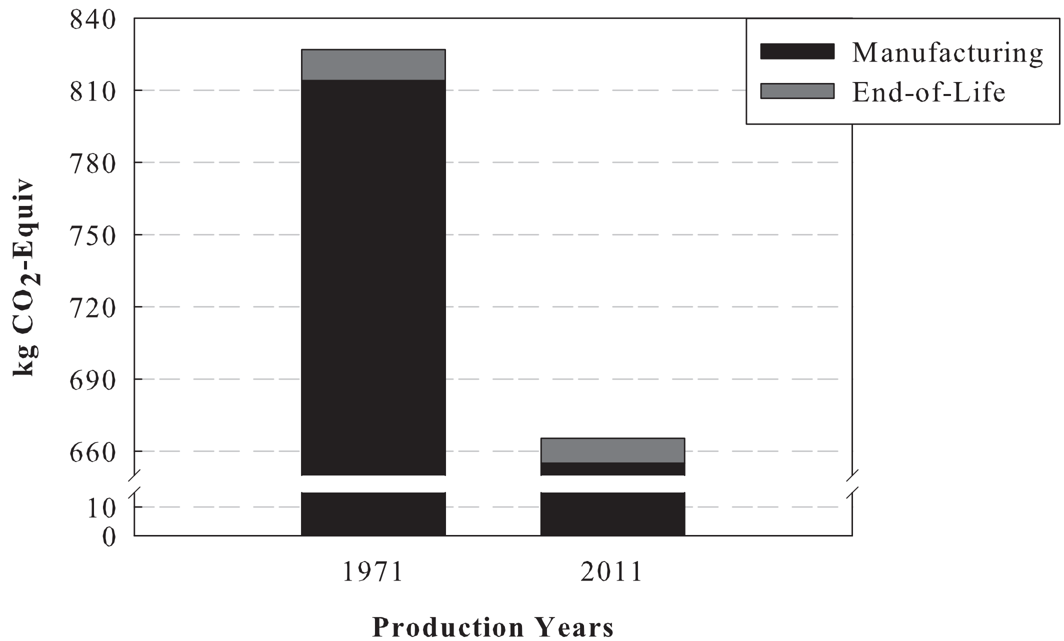

Figure A 21 Global warming potential (in kg CO_2-equiv) of Sample Group 5

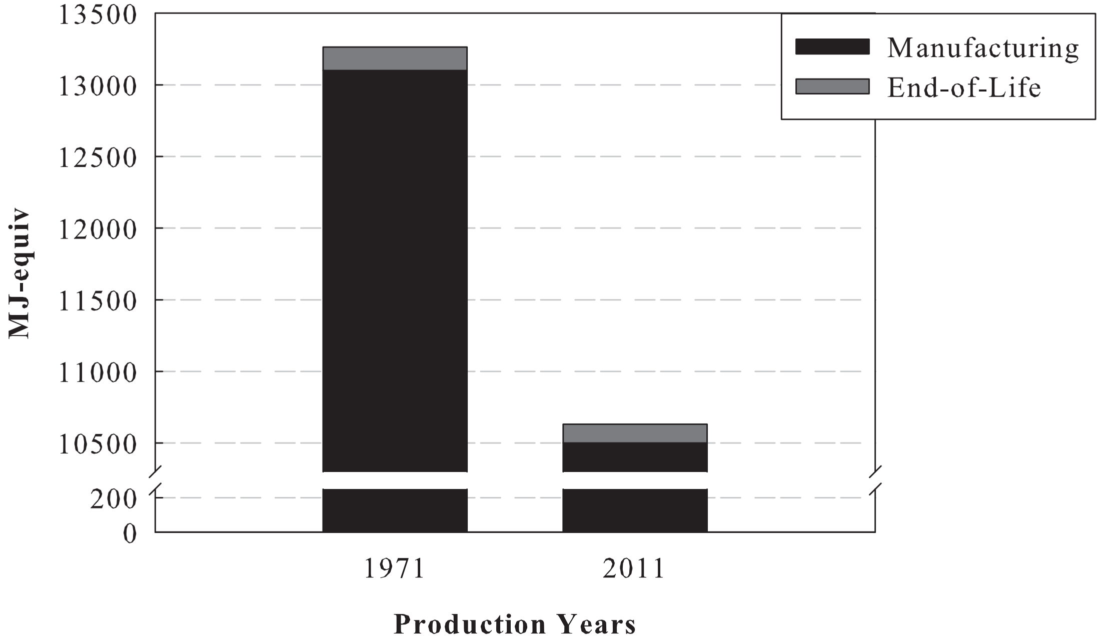

Figure A 22 Fossil fuel consumption (in MJ-equiv) of Sample Group 5

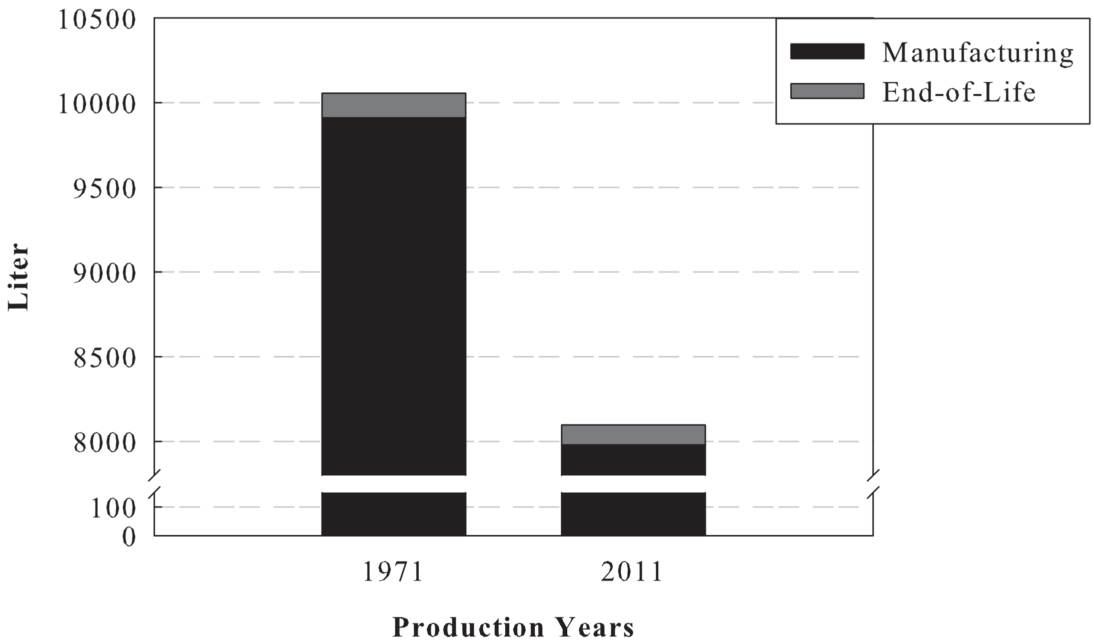

Figure A 23 Water consumption (in liter) of Sample Group 5

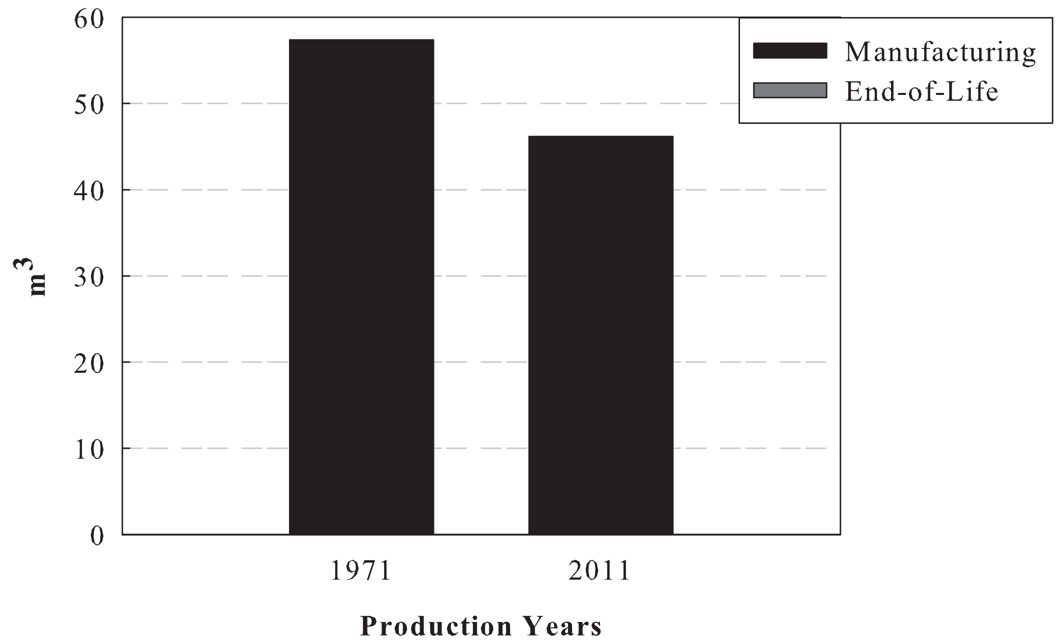

Figure A 24 Biotic resource consumption (in m^3) of Sample Group 5

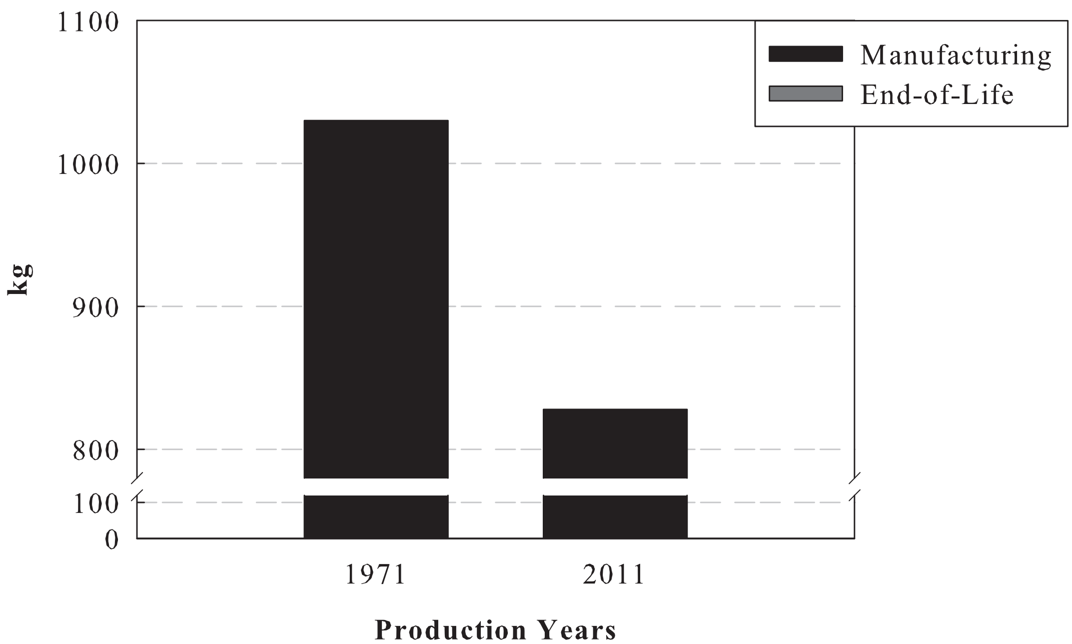

Figure A 25 Mineral resource consumption (in kg) of Sample Group 5

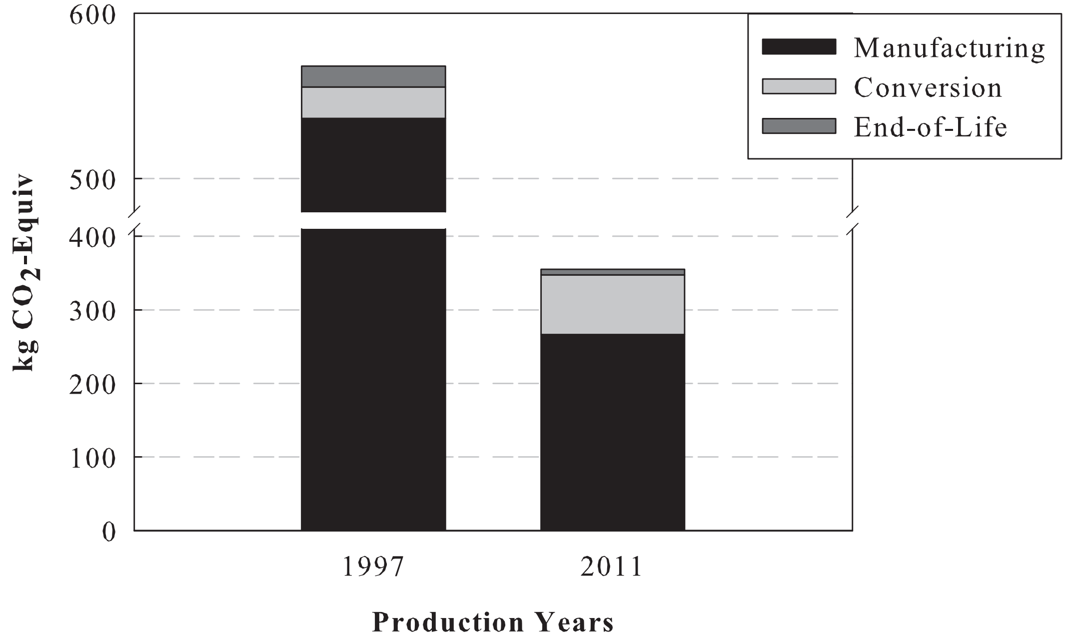

Figure A 26 Global warming potential (in kg CO_2-equiv) of Sample Group 6

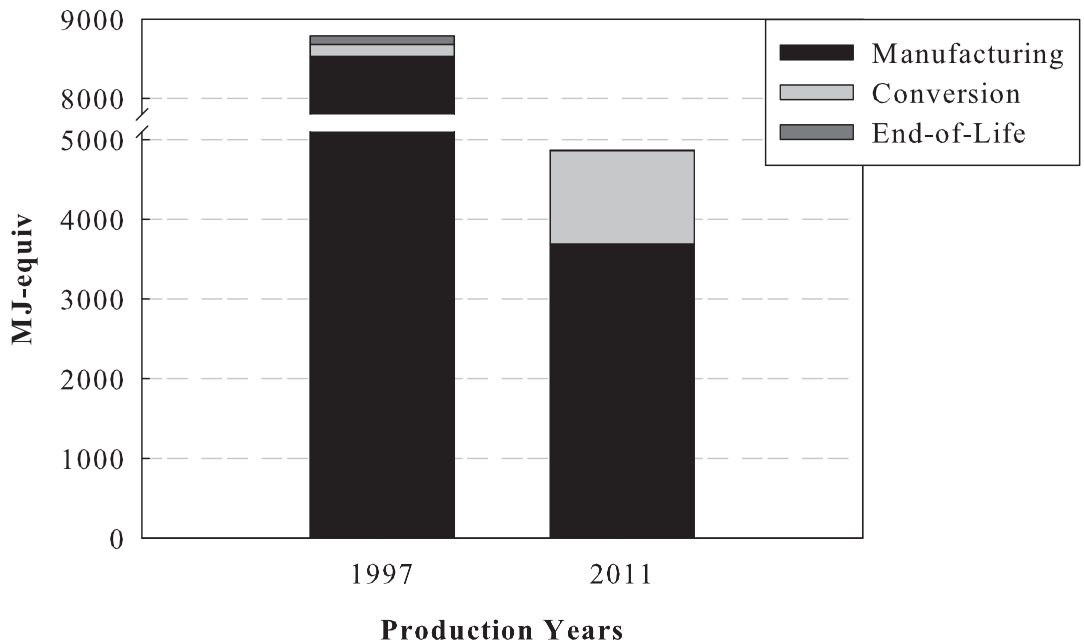

Figure A 27 Fossil fuel consumption (in MJ-equiv) of Sample Group 6

Figure A 28 Water consumption (in liter) of Sample Group 6

Figure A 29 Biotic resource consumption (in m^3) of Sample Group 6

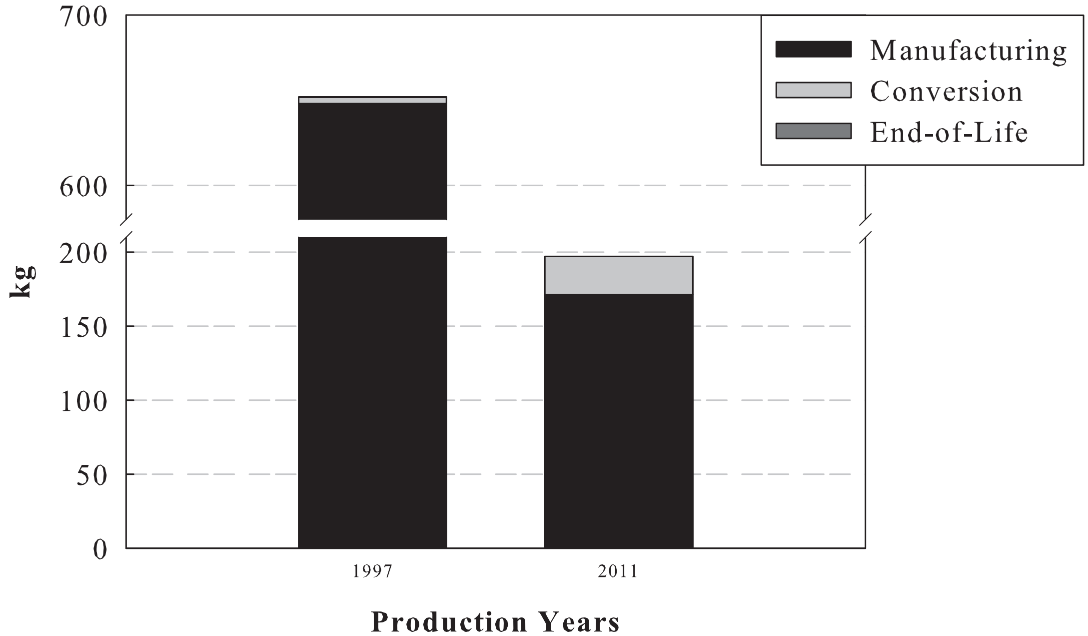

Figure A 30 Mineral resource consumption (in kg) of Sample Group 6

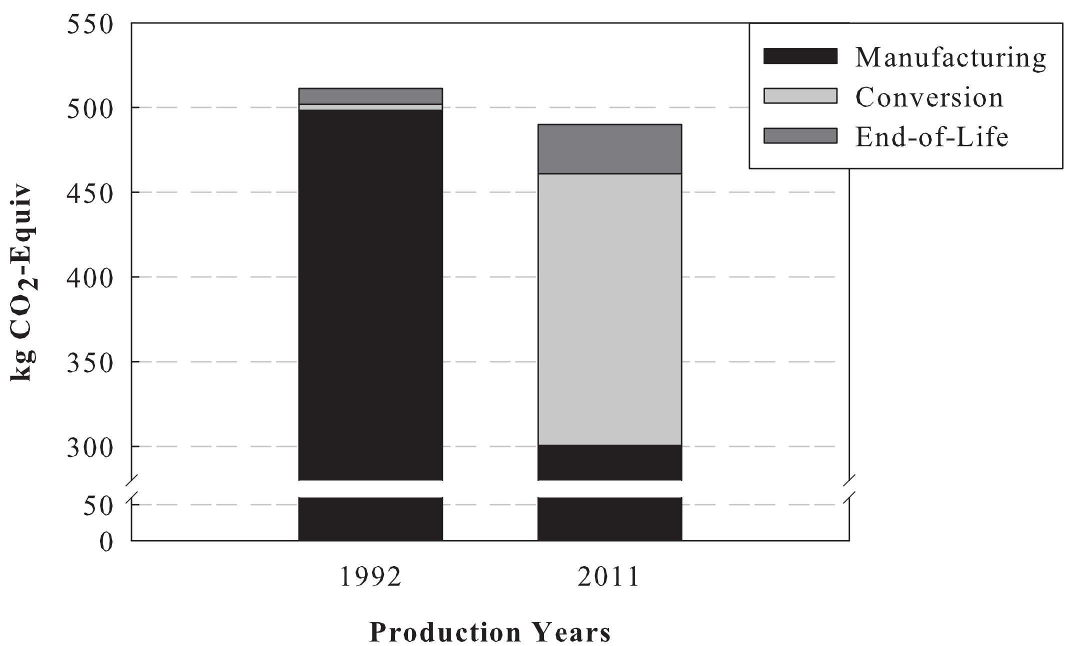

Figure A 31 Global warming potential (in kg CO_2-equiv) of Sample Group 7

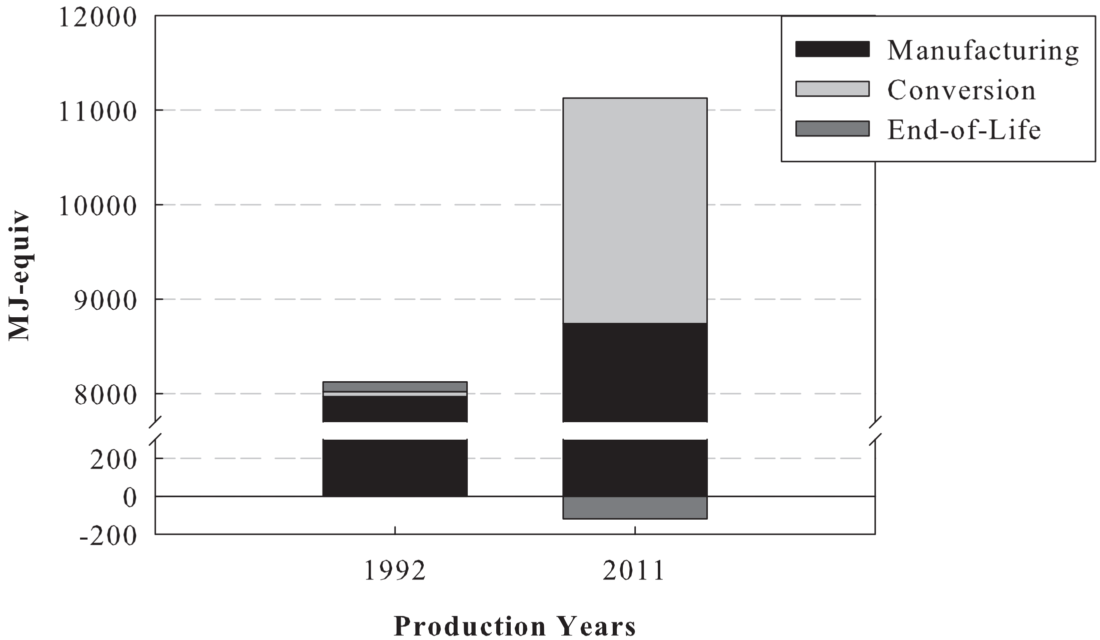

Figure A 32 Fossil fuel consumption (in MJ-equiv) of Sample Group 7

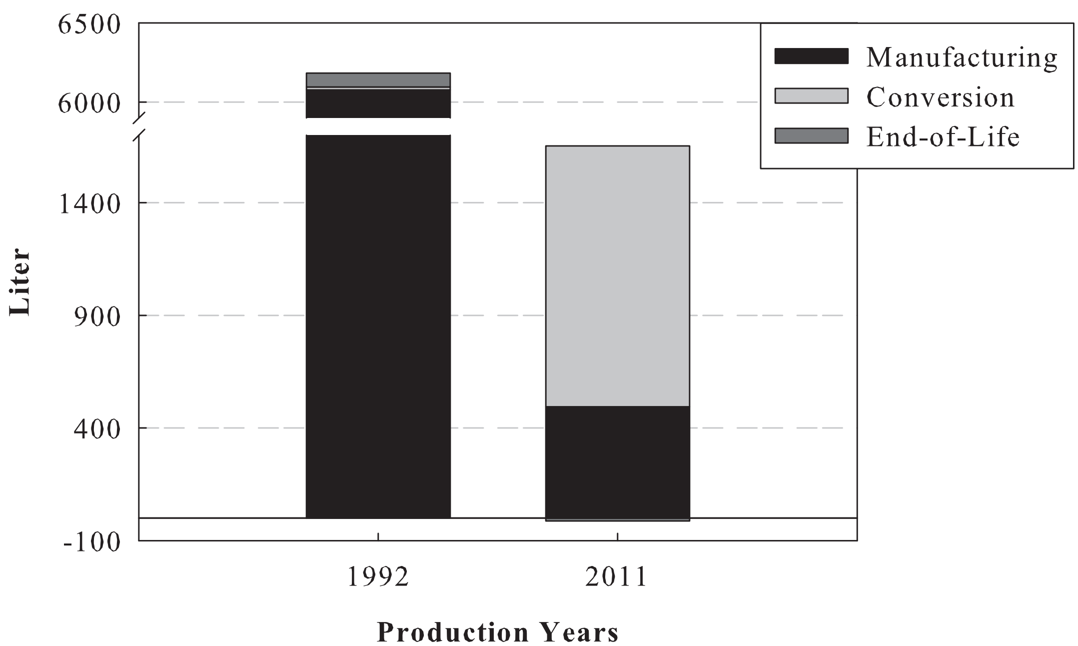

Figure A 33 Water consumption (in liter) of Sample Group 7

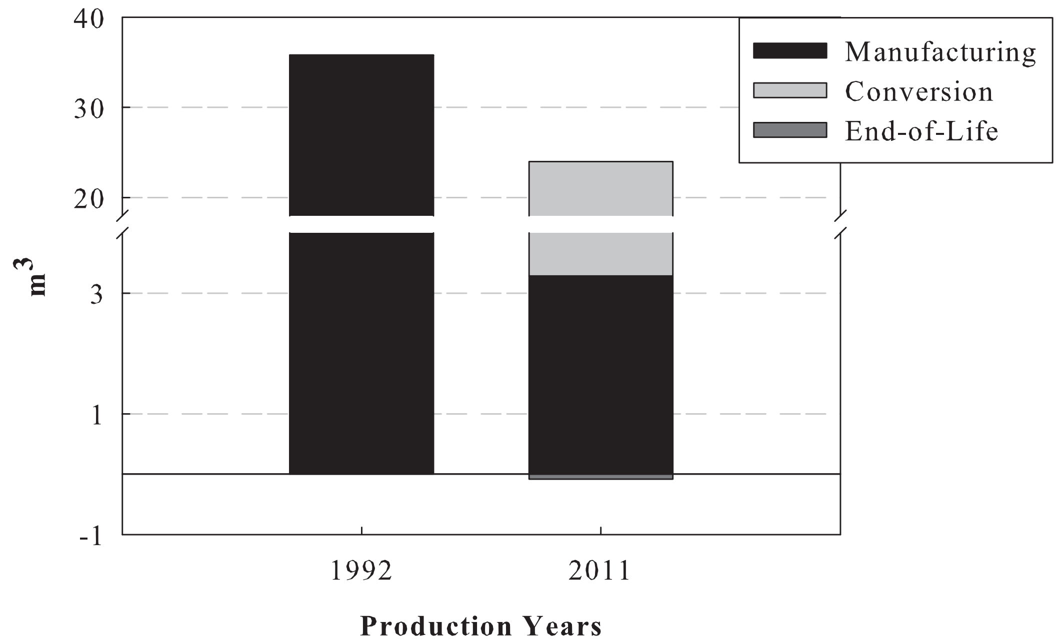

Figure A 34 Biotic resource consumption (in m^3) of Sample Group 7

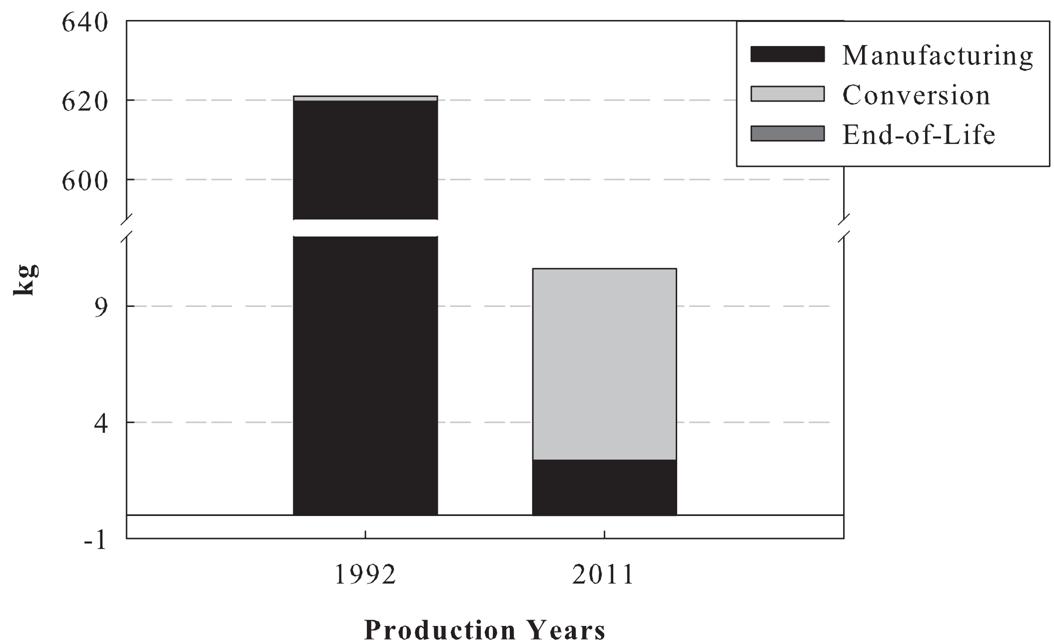

Figure A 35 Mineral resource consumption (in kg) of Sample Group 7

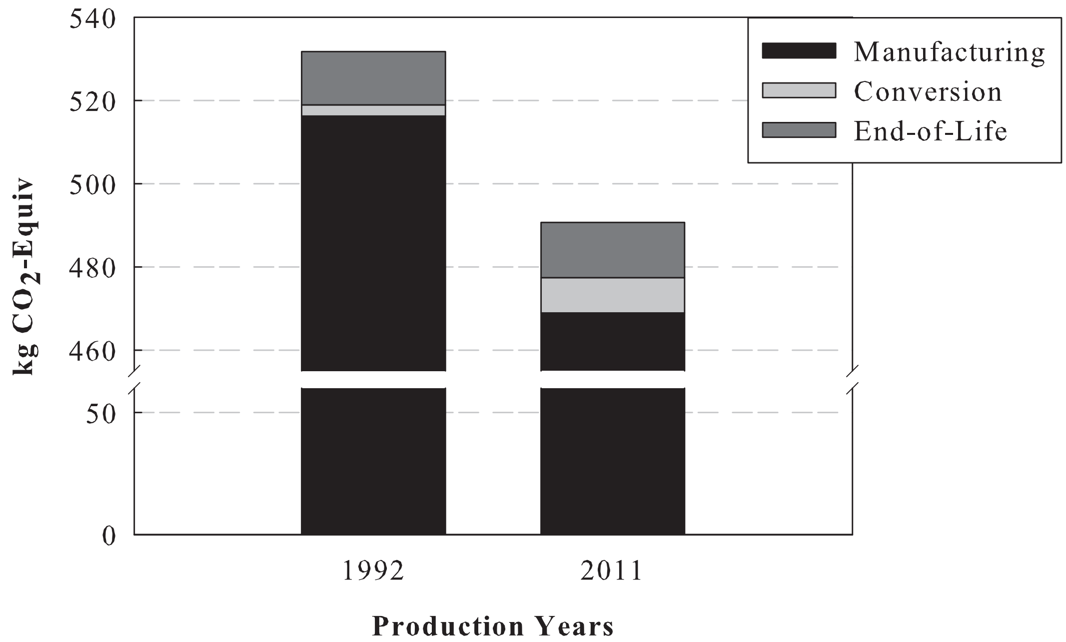

Figure A 36 Global warming potential (in kg CO_2-equiv) of Sample Group 8

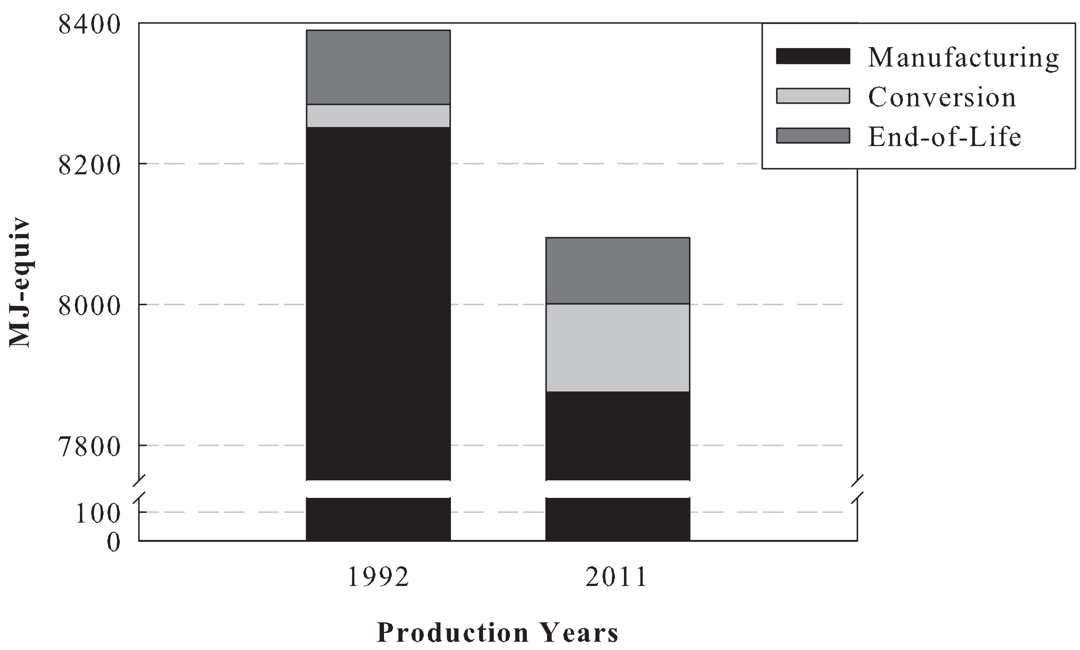

Figure A 37 Fossil fuel consumption (in MJ-equiv) of Sample Group 8

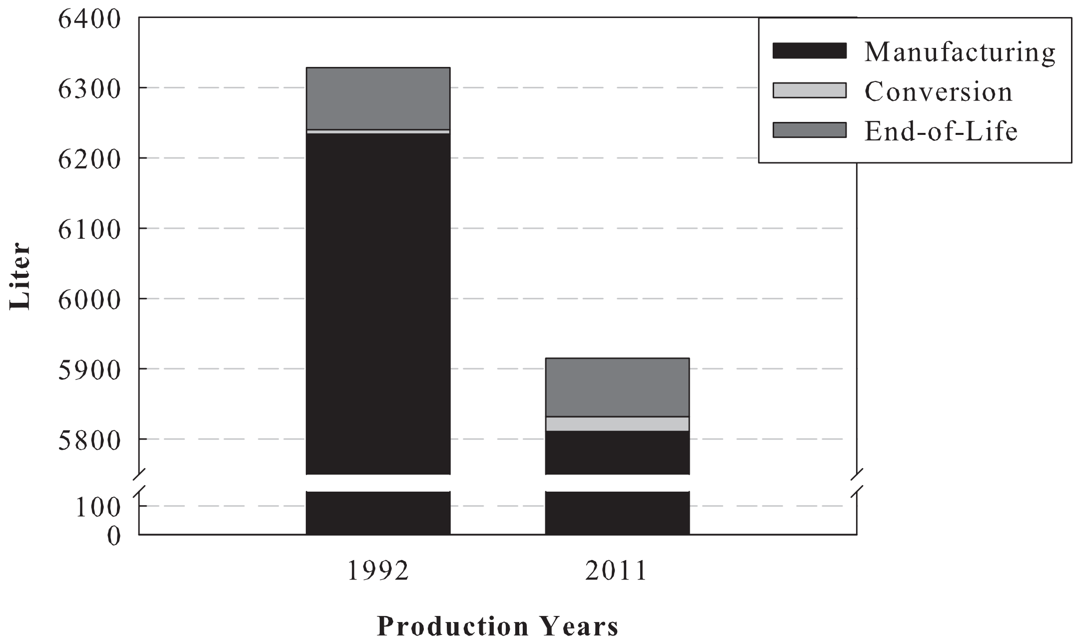

Figure A 38 Water consumption (in liter) of Sample Group 8

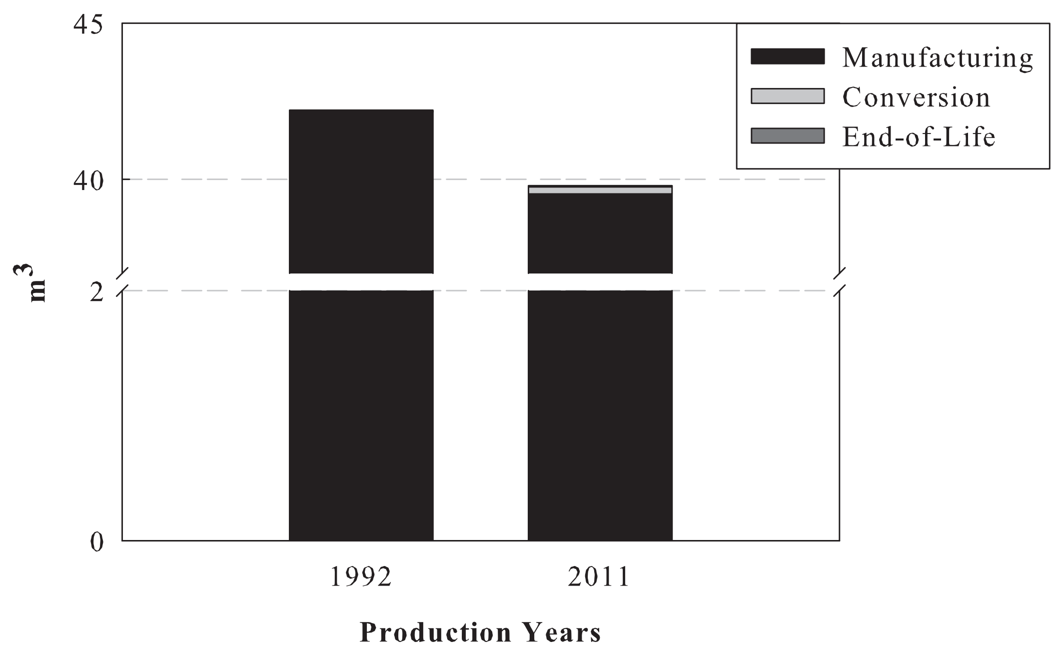

Figure A 39 Biotic resource consumption (in m^3) of Sample Group 8

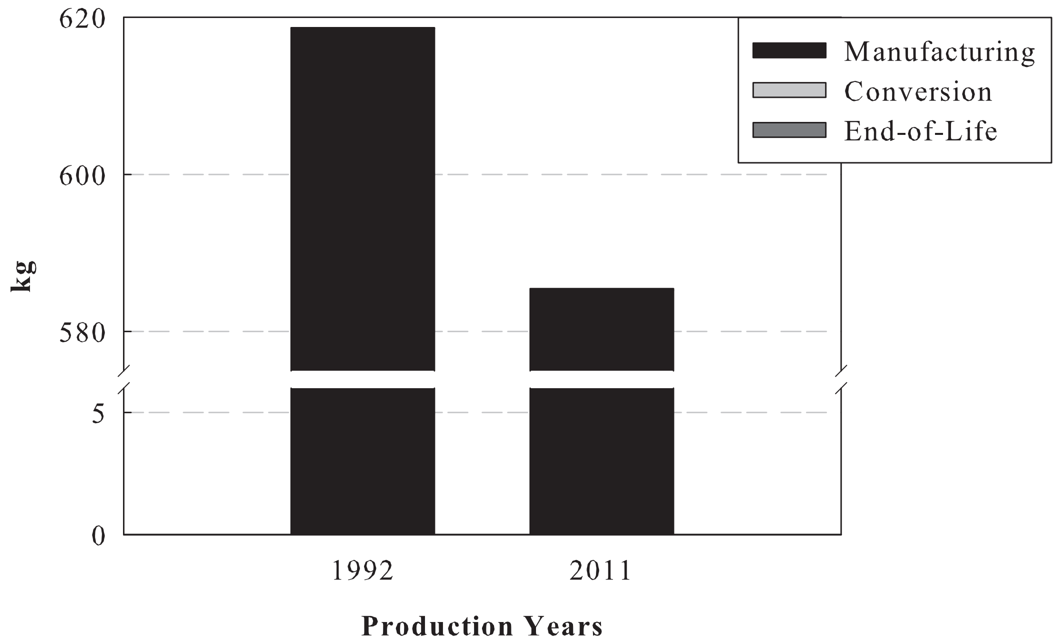

Figure A 40 Mineral resource consumption (in kg) of Sample Group 8

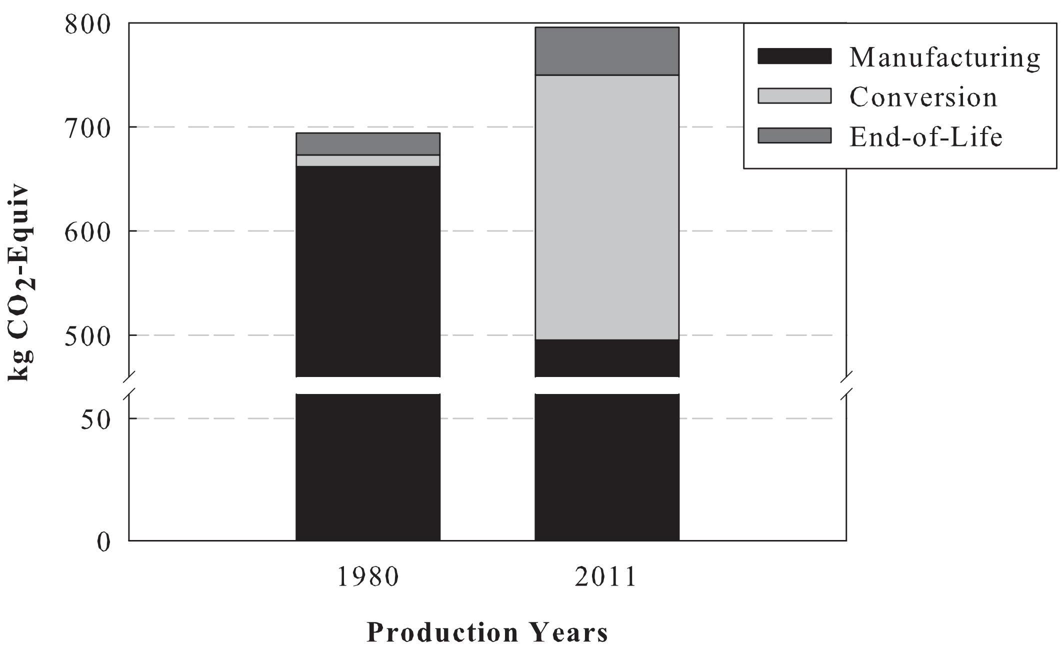

Figure A 41 Global warming potential (in kg CO_2-equiv) of Sample Group 9

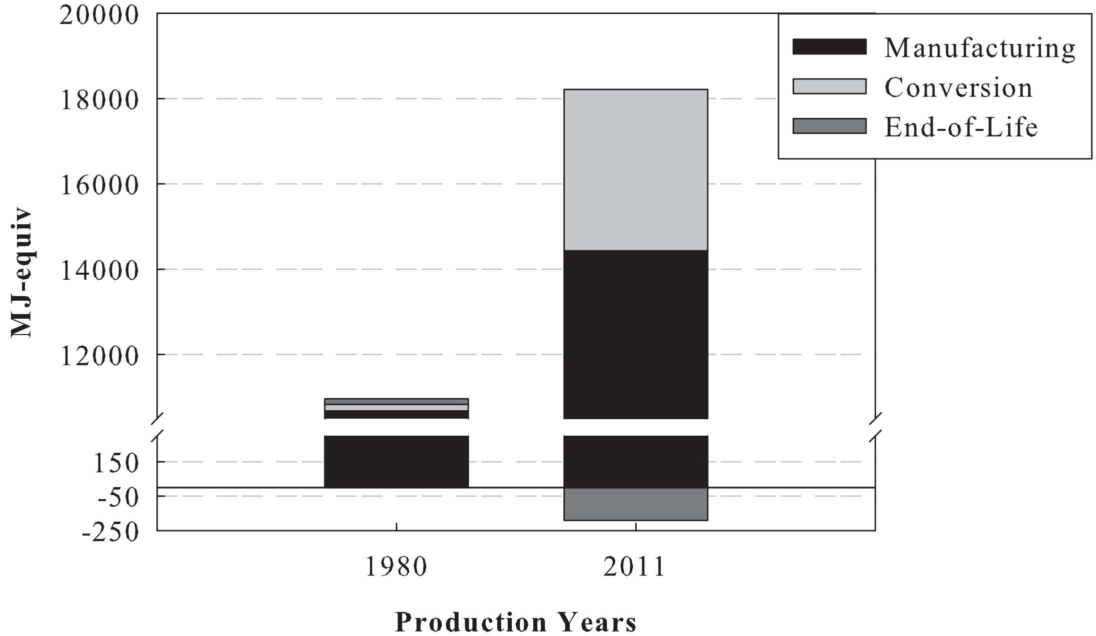

Figure A 42 Fossil fuel consumption (in MJ-equiv) of Sample Group 9

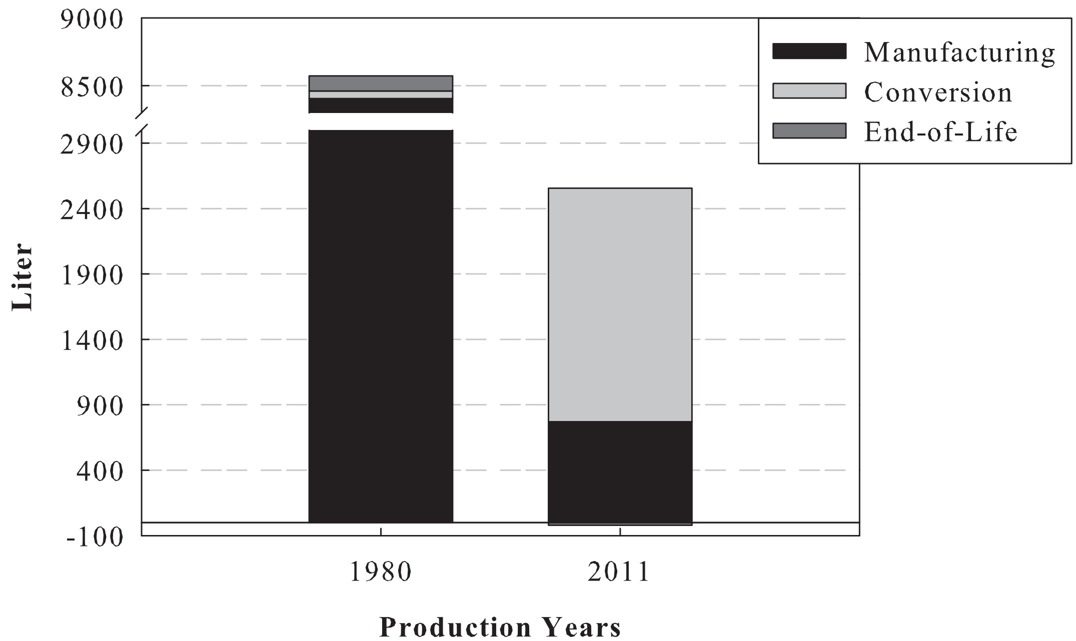

Figure A 43 Water consumption (in liter) of Sample Group 9

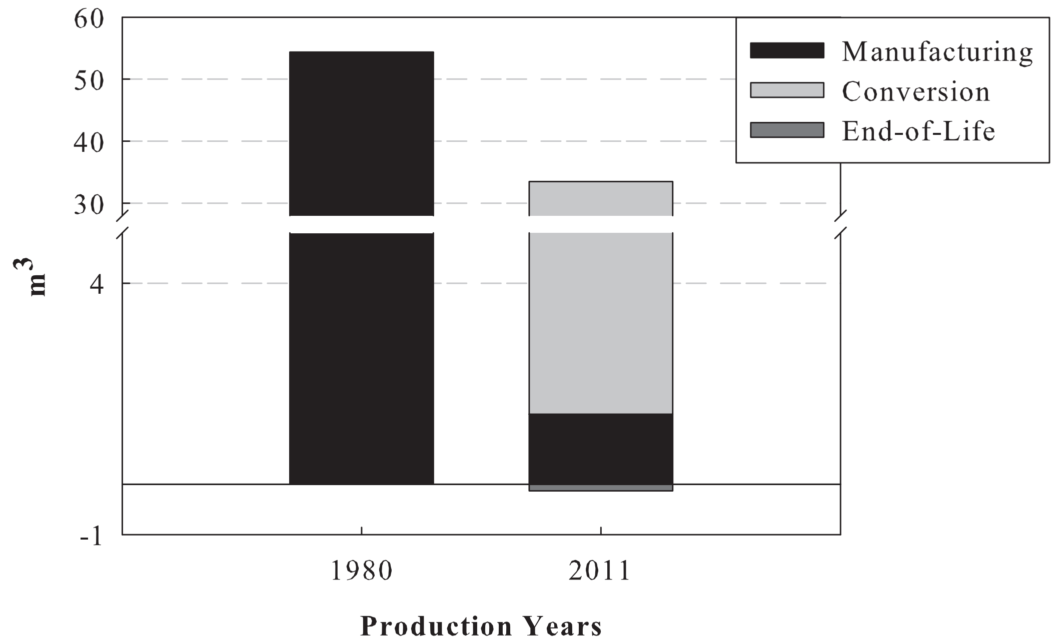

Figure A 44 Biotic resource consumption (in m^3) of Sample Group 9

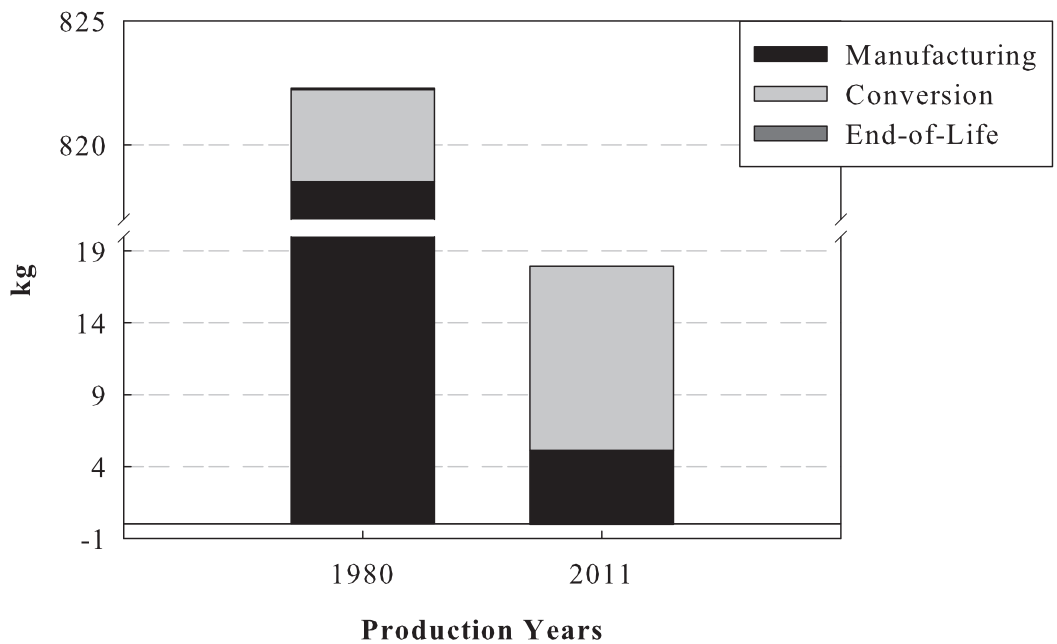

Figure A 45 Mineral resource consumption (in kg) of Sample Group 9

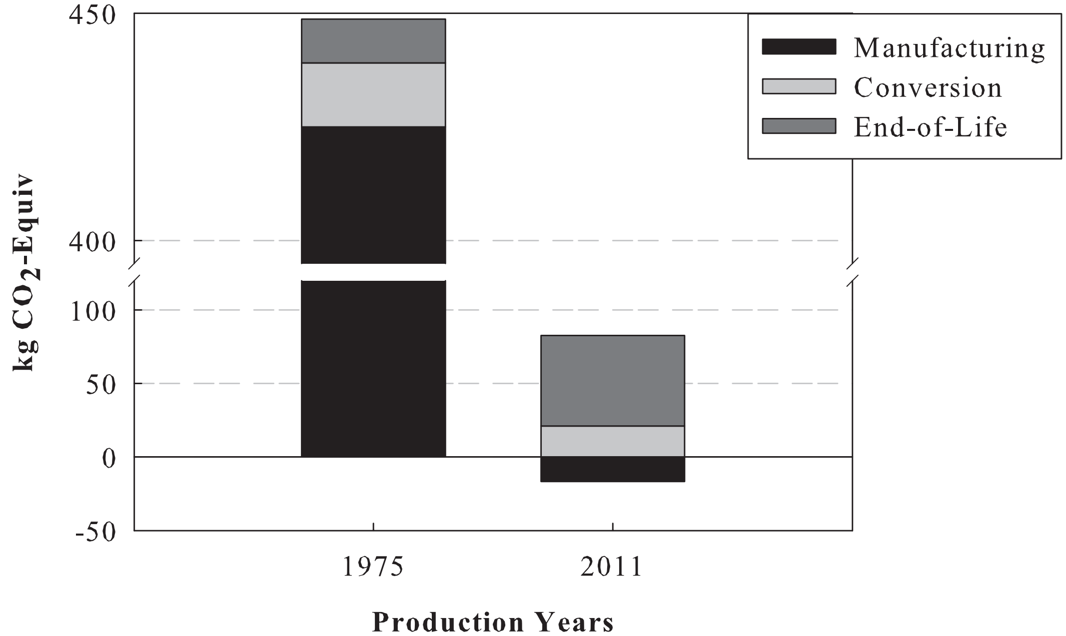

Figure A 46 Global warming potential (in kg CO_2-equiv) of Sample Group 10

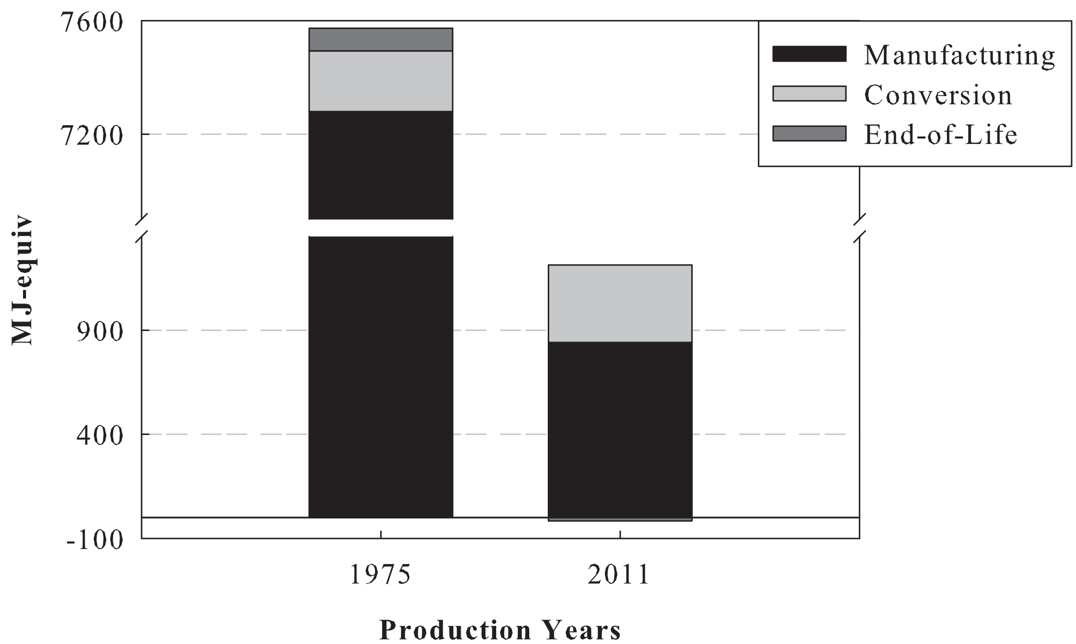

Figure A 47 Fossil fuel consumption (in MJ-equiv) of Sample Group 10

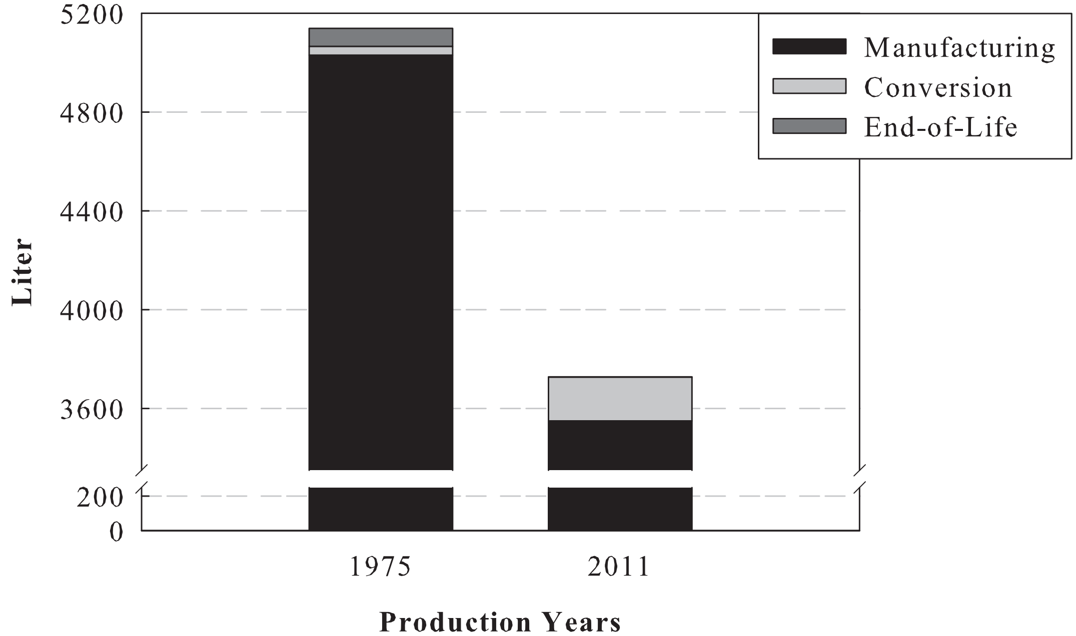

Figure A 48 Water consumption (in liter) of Sample Group 10

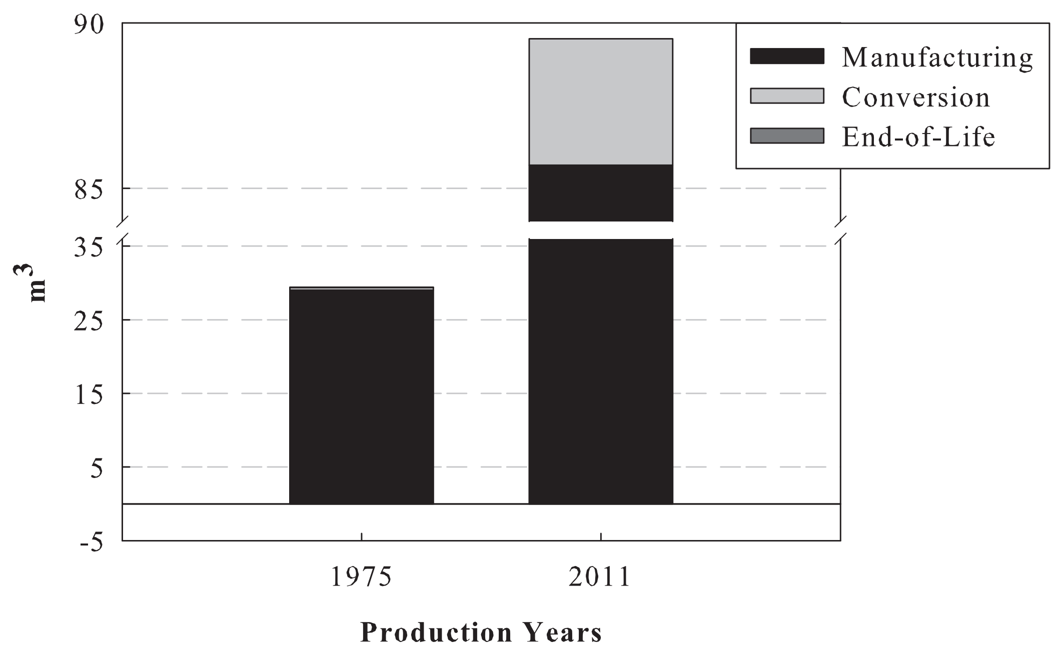

Figure A 49 Biotic resource consumption (in m^3) of Sample Group 10

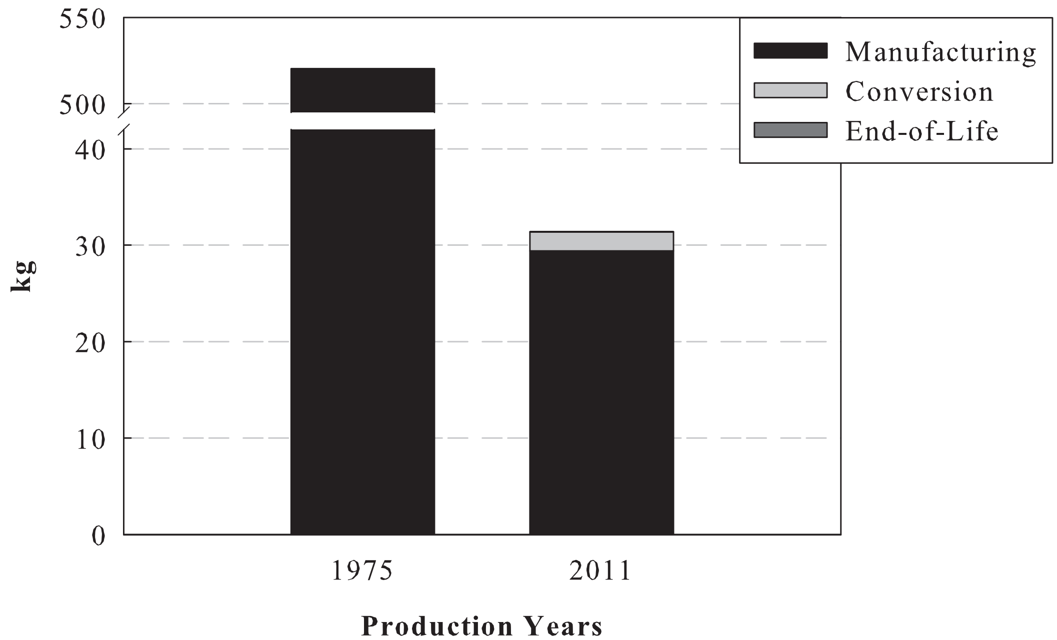

Figure A 50 Mineral resource consumption (in kg) of Sample Group 10

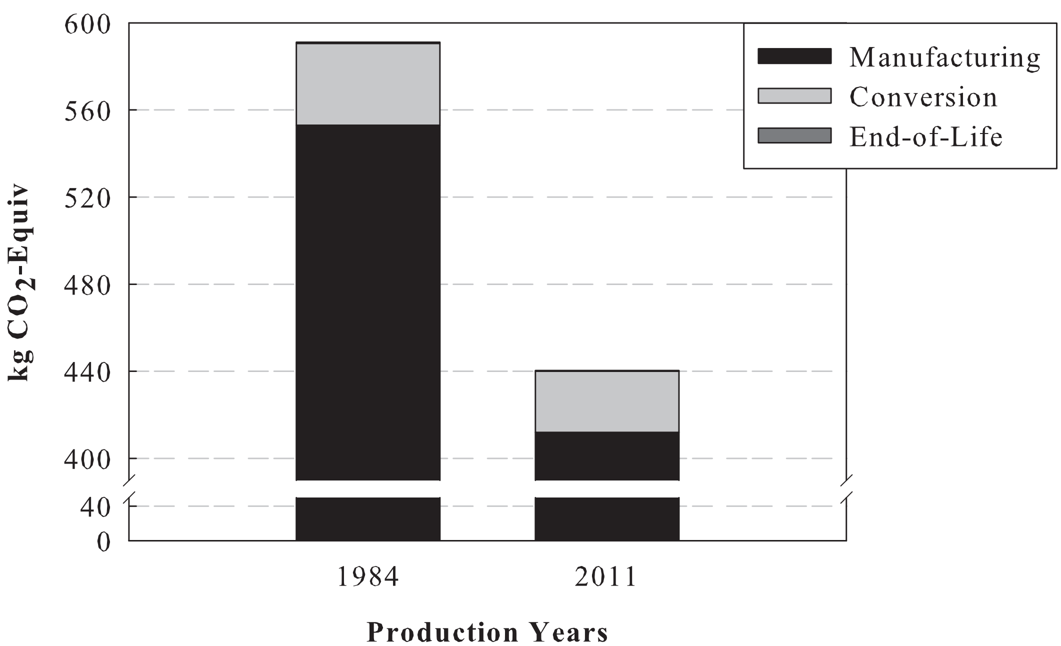

Figure A 51 Global warming potential (in kg CO_2-equiv) of Sample Group 11

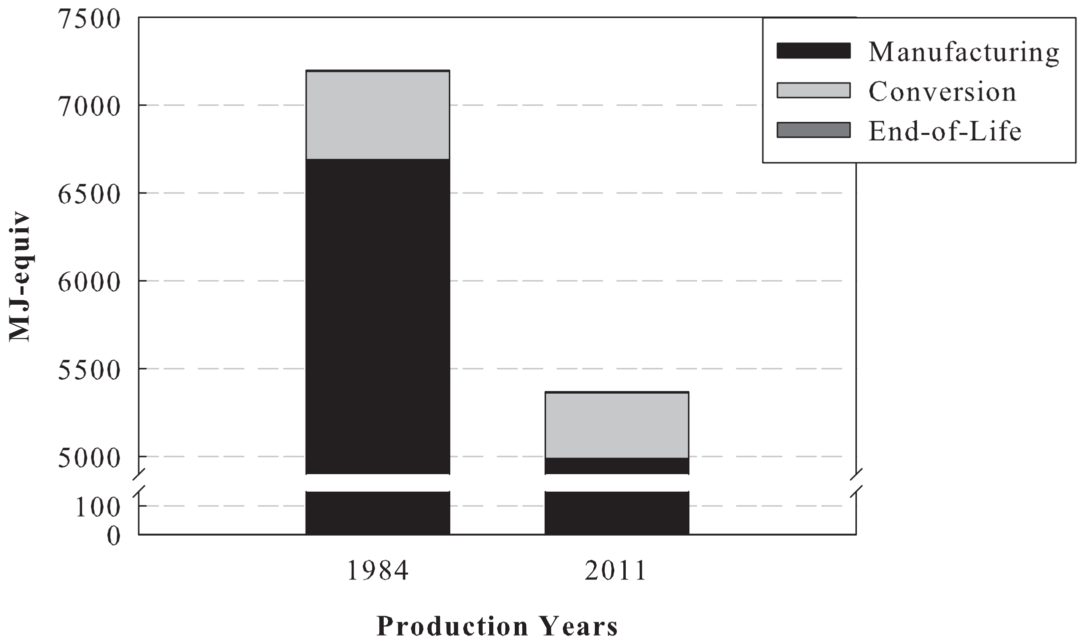

Figure A 52 Fossil fuel consumption (in MJ-equiv) of Sample Group 11

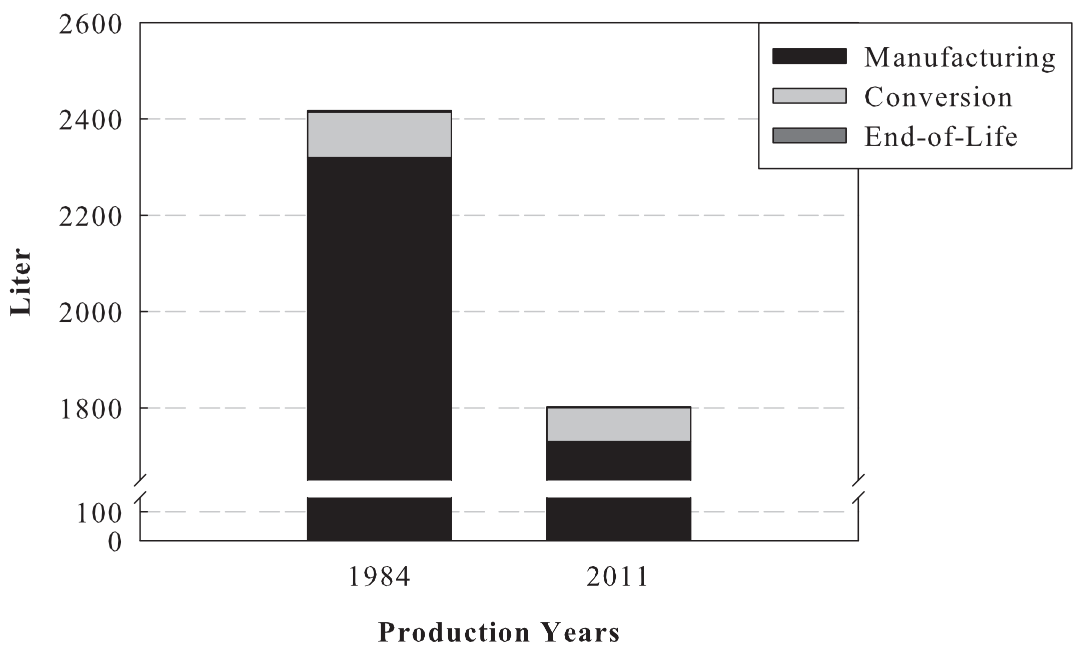

Figure A 53 Water consumption (in liter) of Sample Group 11

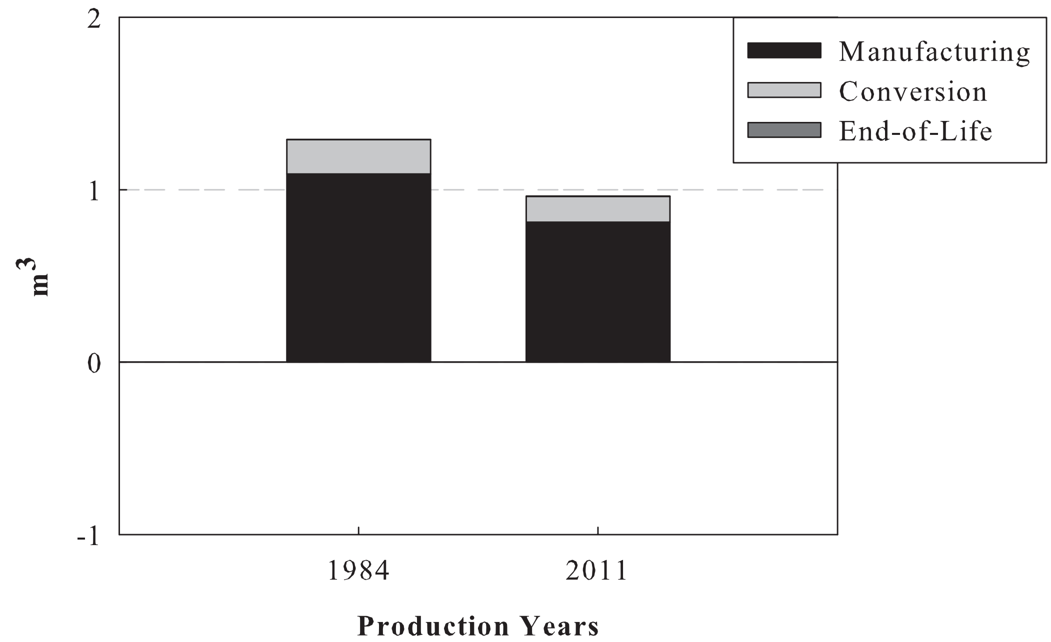

Figure A 54 Biotic resource consumption (in m^3) of Sample Group 11

Figure A 55 Mineral resource consumption (in kg) of Sample Group 11

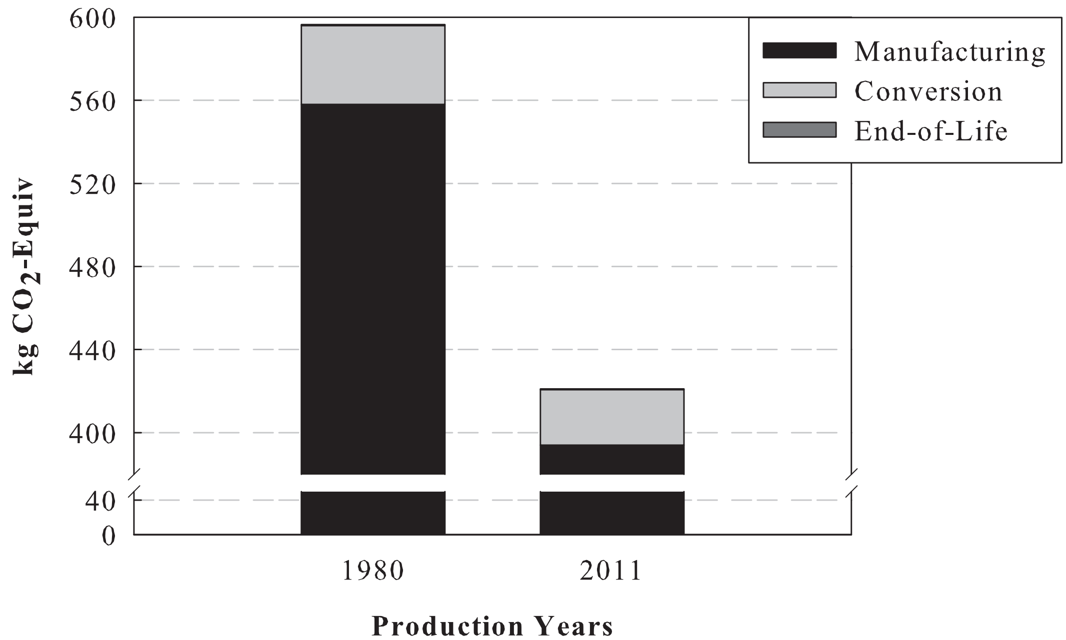

Figure A 56 Global warming potential (in kg CO_2-equiv) of Sample Group 12

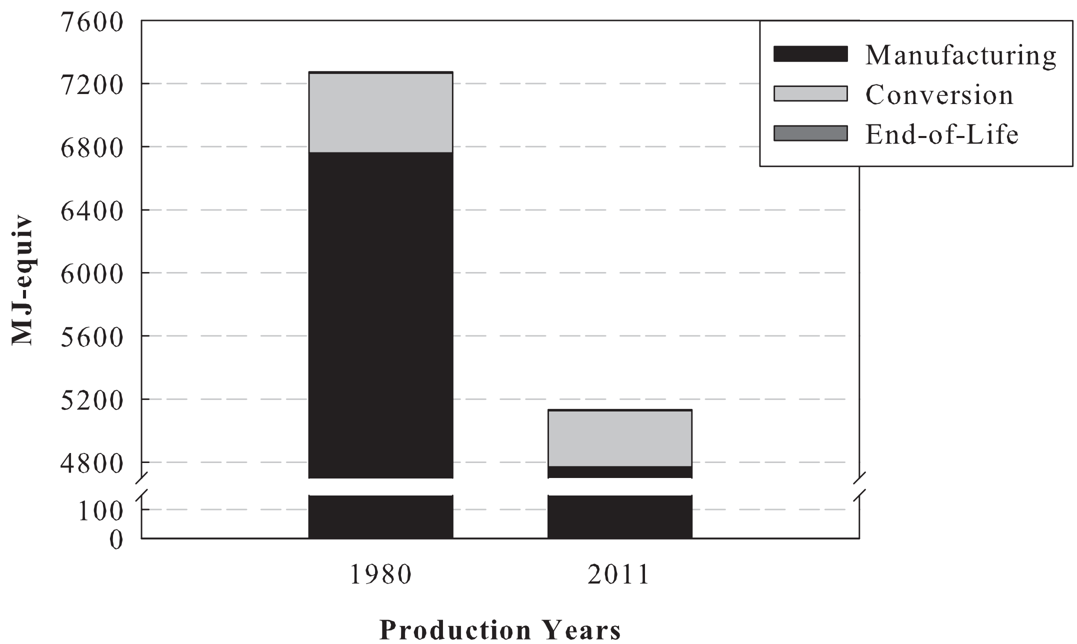

Figure A 57 Fossil fuel consumption (in MJ-equiv) of Sample Group 12

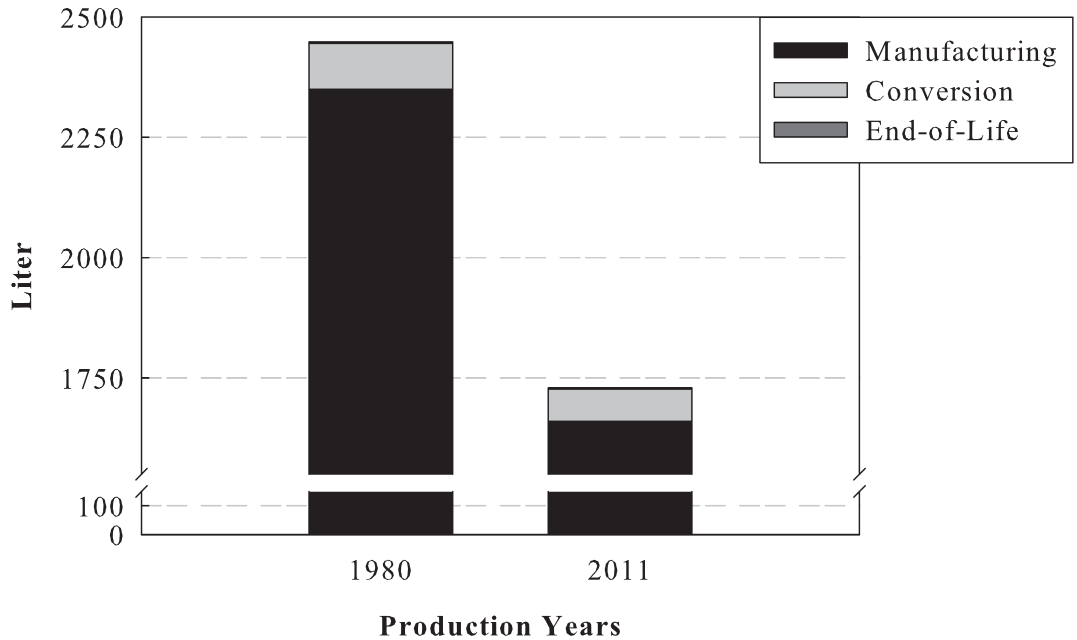

Figure A 58 Water consumption (in liter) of Sample Group 12

Figure A 59 Biotic resource consumption (in m^3) of Sample Group 12

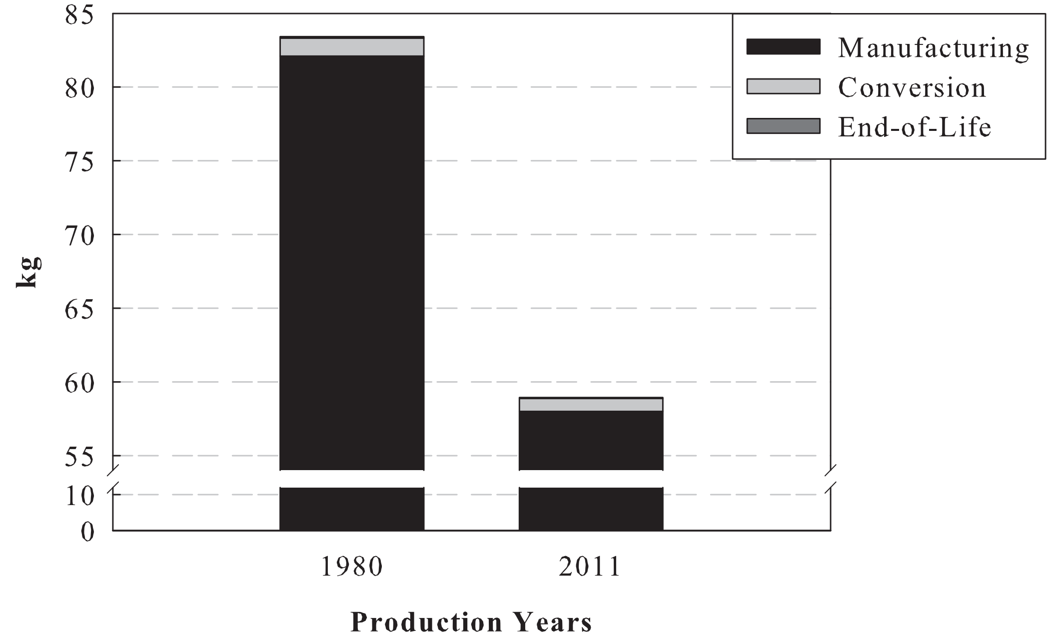

Figure A 60 Mineral resource consumption (in kg) of Sample Group 12

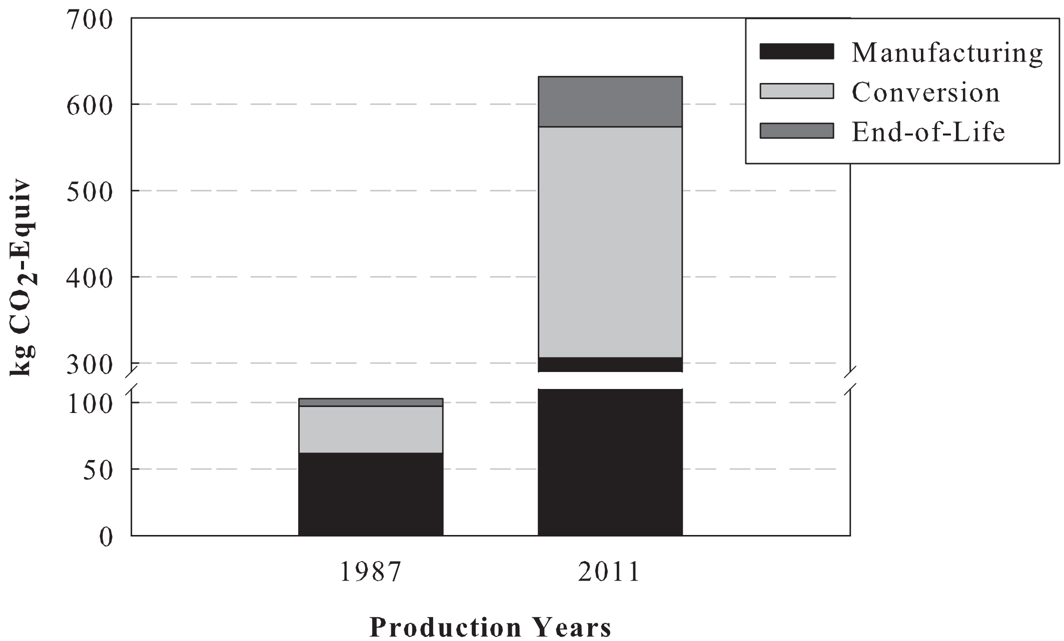

Figure A 61 Global warming potential (in kg CO_2-equiv) of Sample Group 13

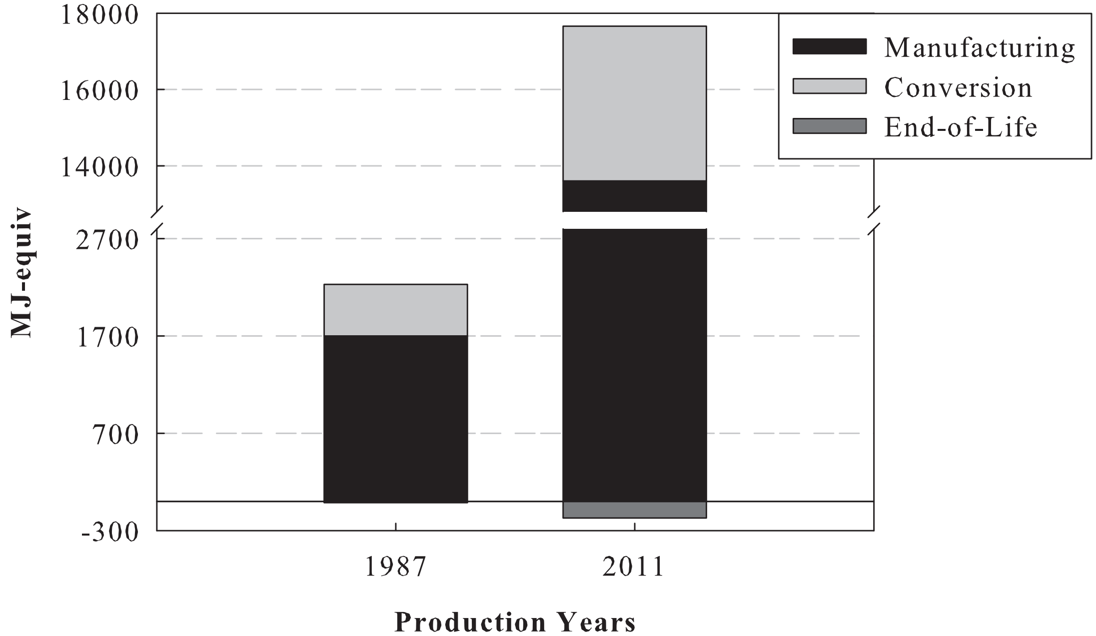

Figure A 62 Fossil fuel consumption (in MJ-equiv) of Sample Group 13

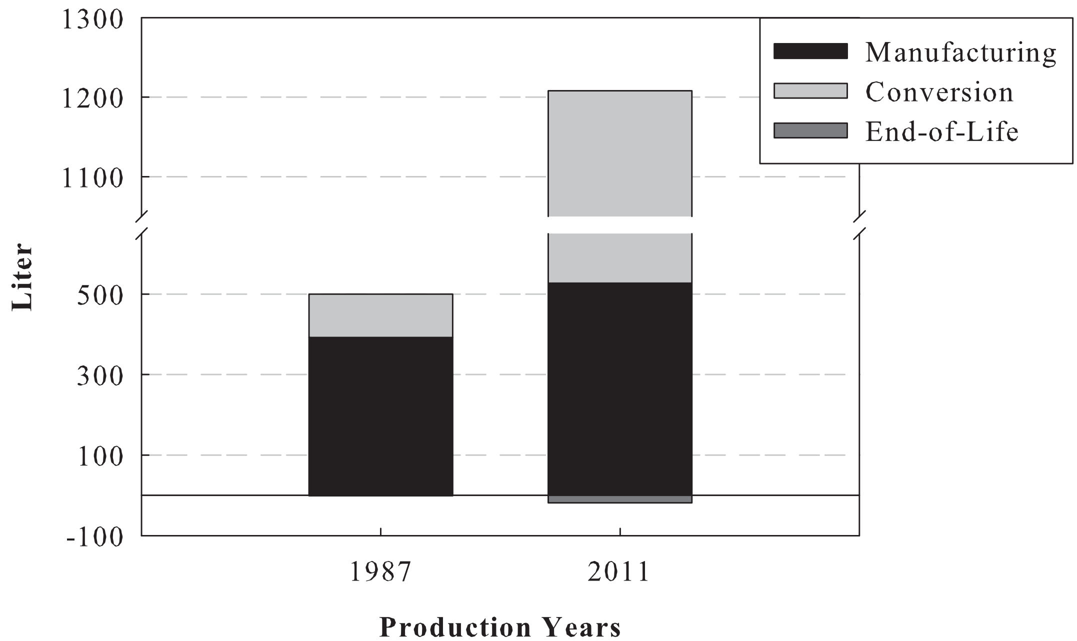

Figure A 63 Water consumption (in liter) of Sample Group 13

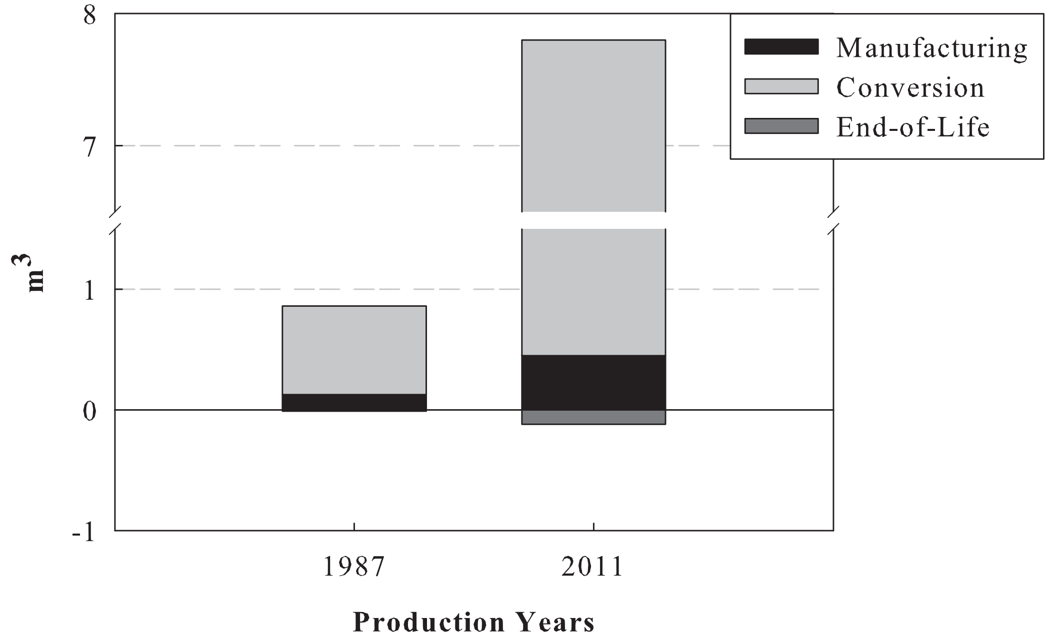

Figure A 64 Biotic resource consumption (in m^3) of Sample Group 13

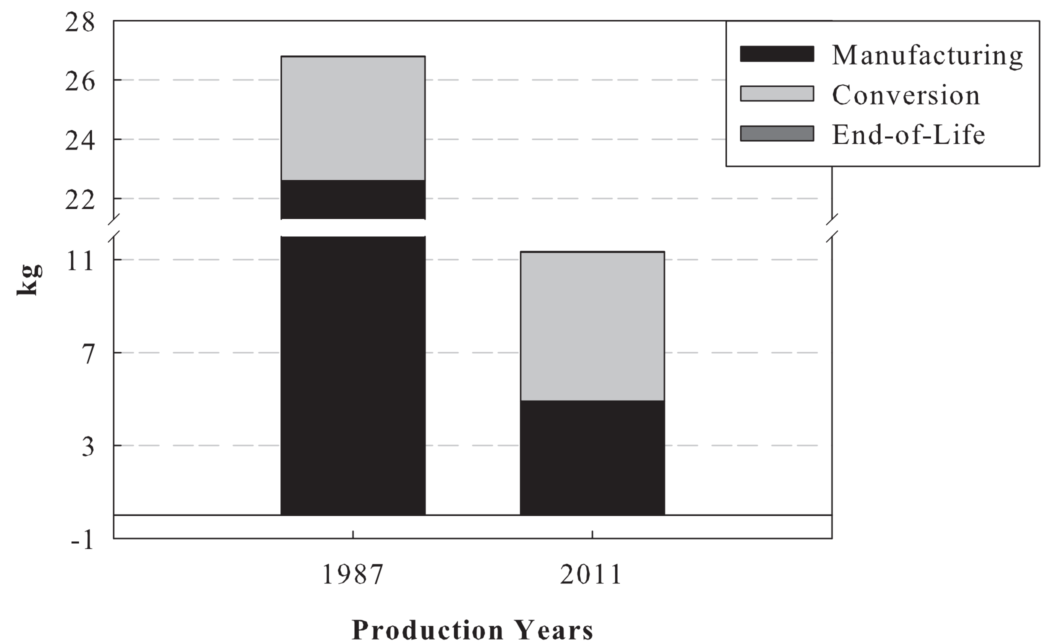

Figure A 65 Mineral resource consumption (in kg) of Sample Group 13

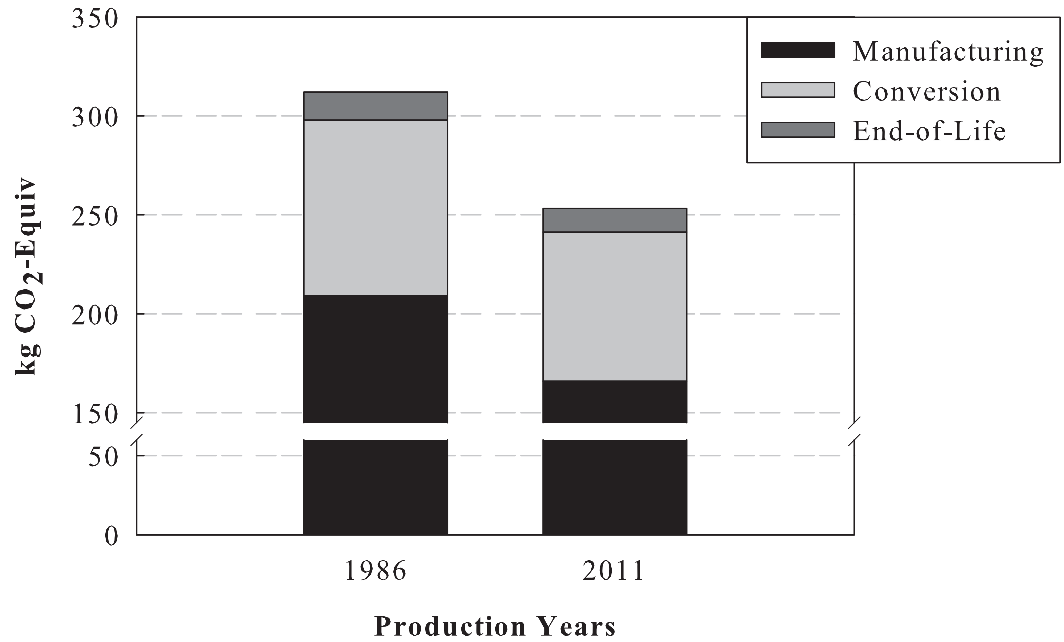

Figure A 66 Global warming potential (in kg CO_2-equiv) of Sample Group 14

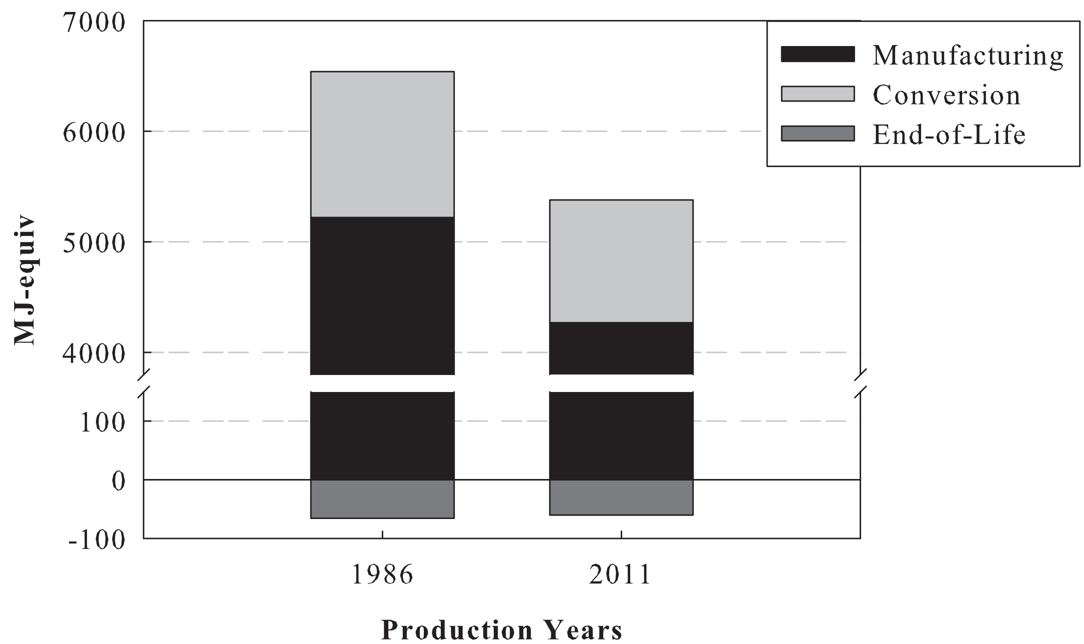

Figure A 67 Fossil fuel consumption (in MJ-equiv) of Sample Group 14

Figure A 68 Water consumption (in liter) of Sample Group 14

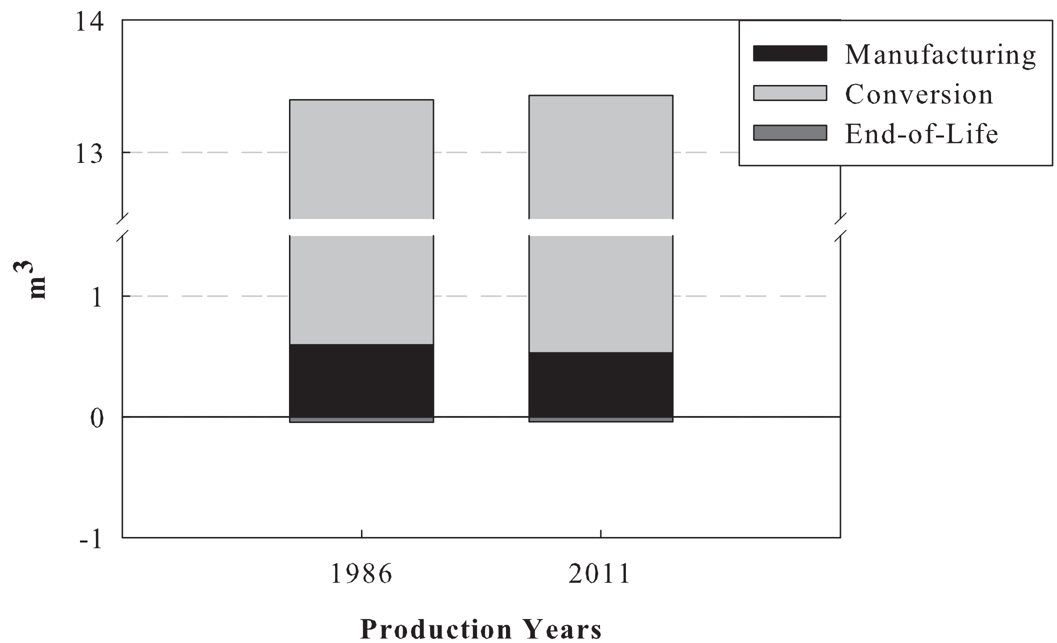

Figure A 69 Biotic resource consumption (in m^3) of Sample Group 14

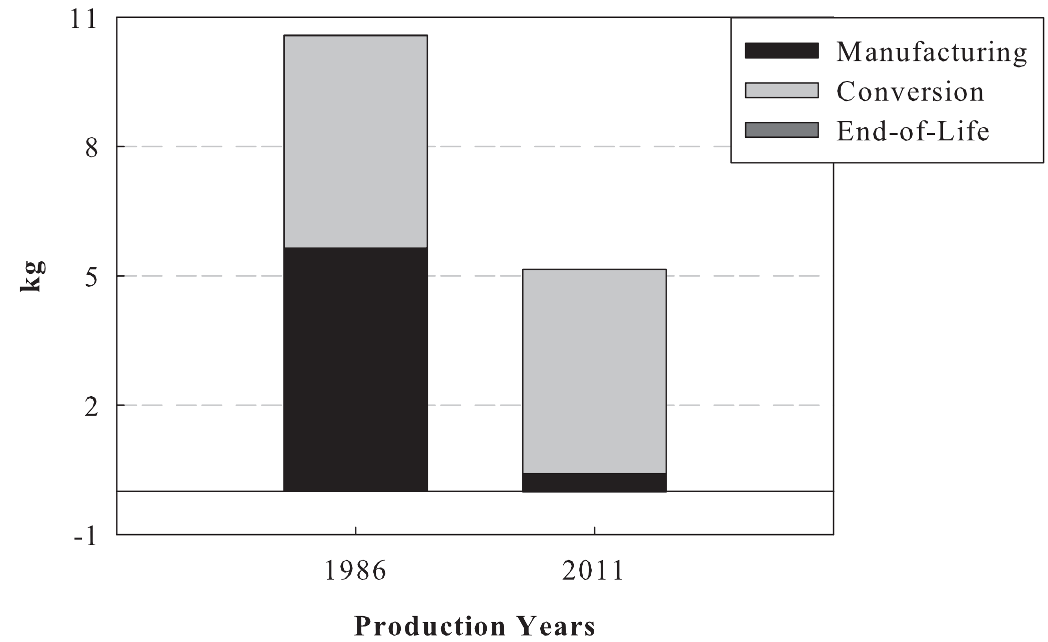

Figure A 70 Mineral resource consumption (in kg) of Sample Group 14

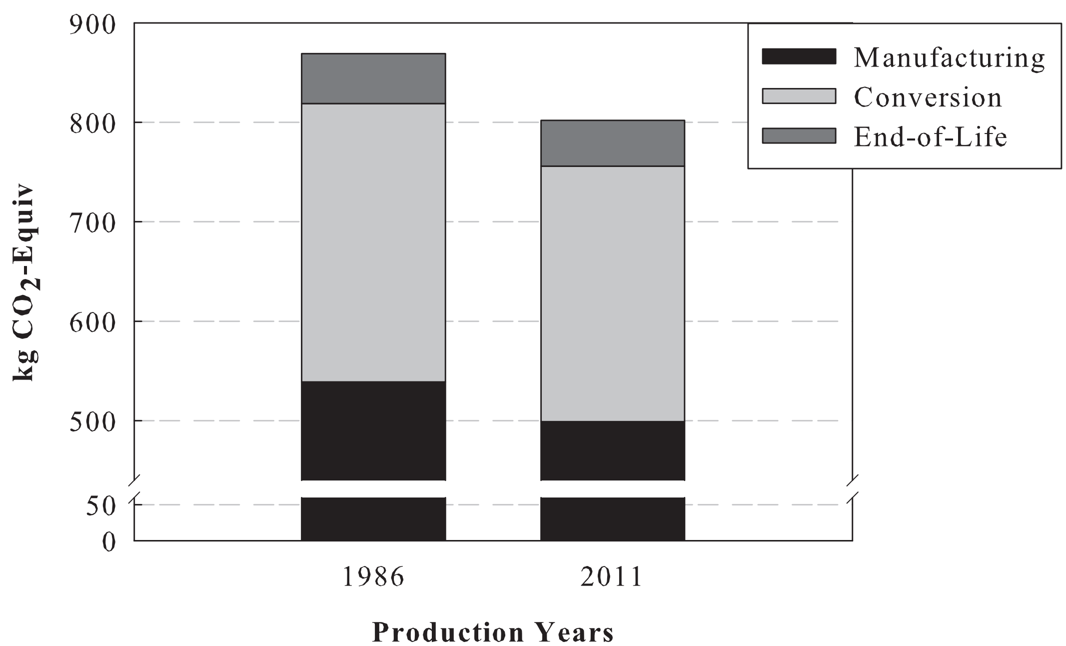

Figure A 71 Global warming potential (in kg CO_2-equiv) of Sample Group 15

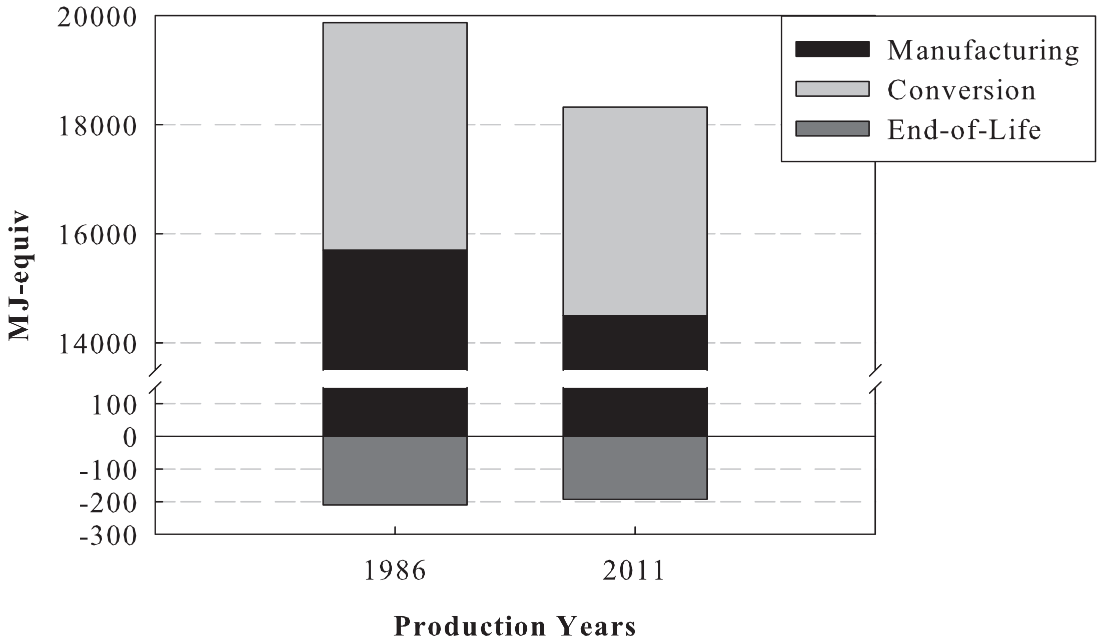

Figure A 72 Fossil fuel consumption (in MJ-equiv) of Sample Group 15

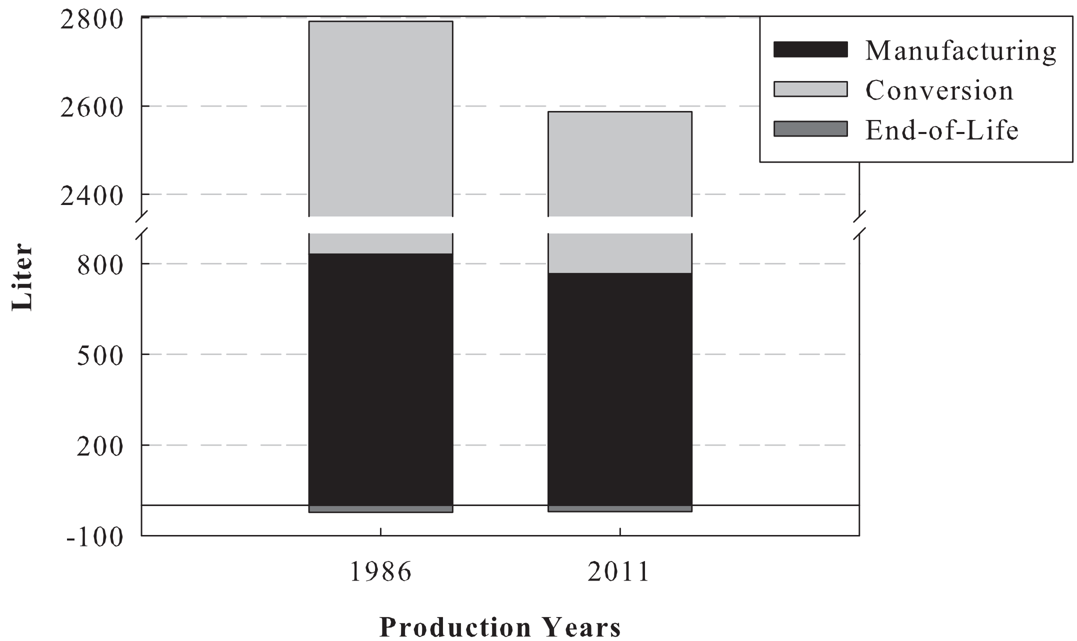

Figure A 73 Water consumption (in liter) of Sample Group 15

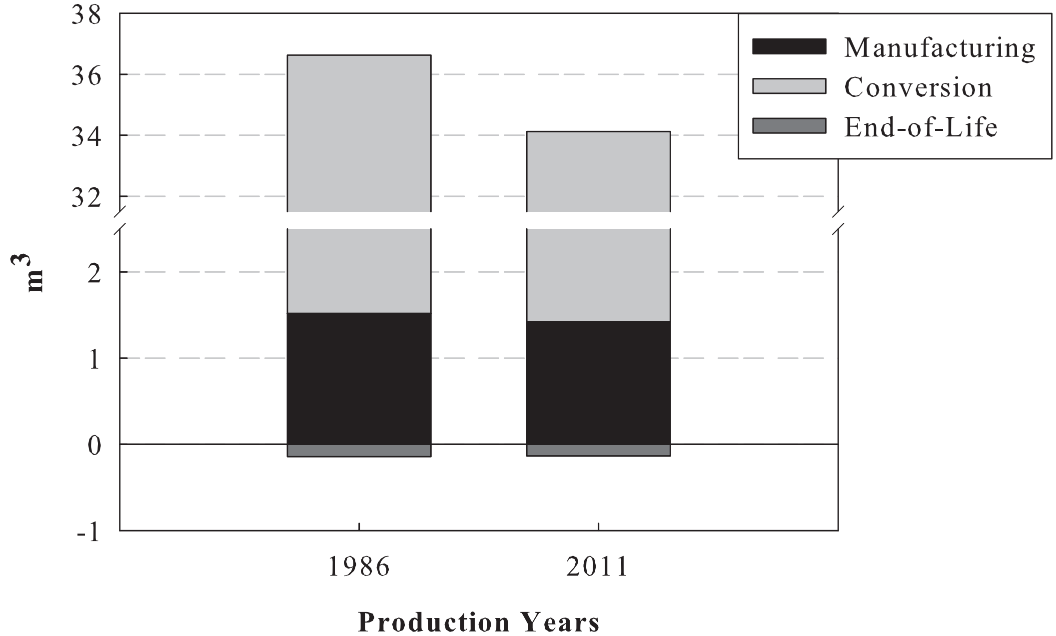

Figure A 74 Biotic resource consumption (in m^3) of Sample Group 15

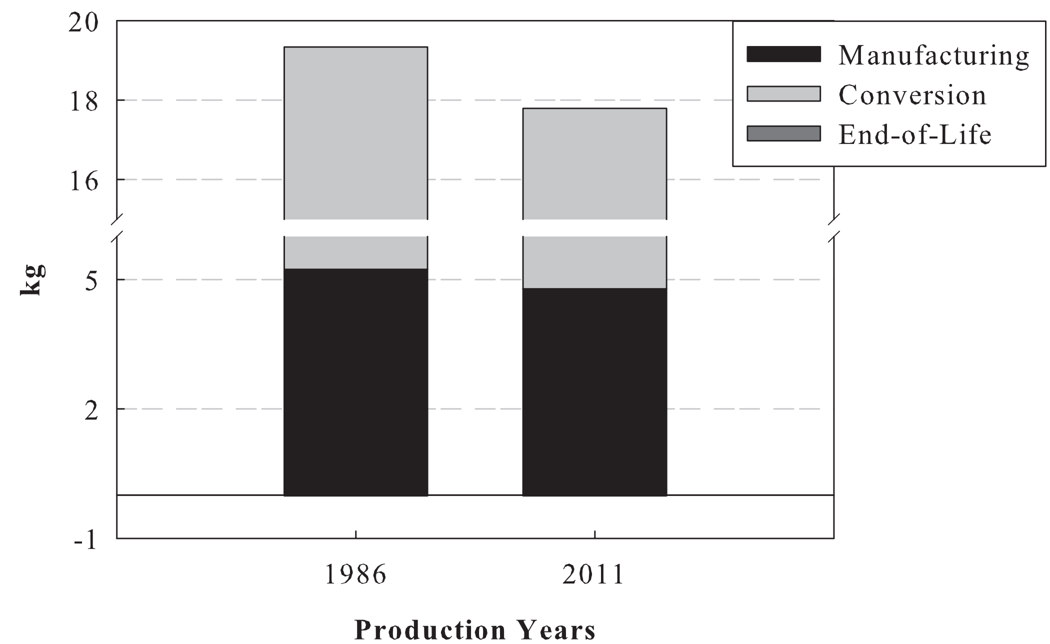

Figure A 75 Mineral resource consumption (in kg) of Sample Group 15

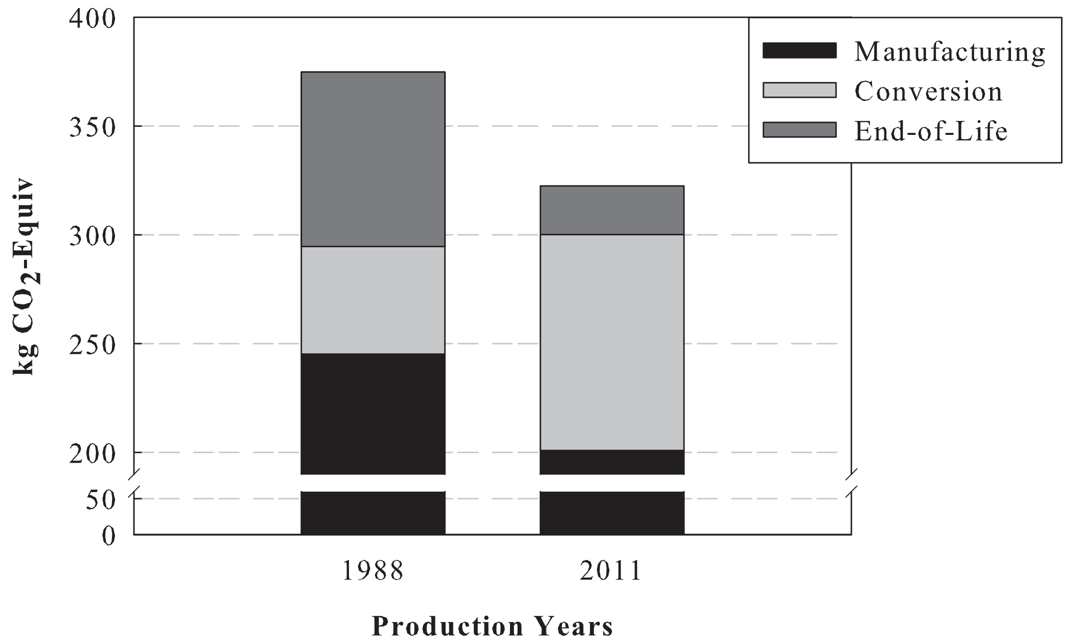

Figure A 76 Global warming potential (in kg CO_2-equiv) of Sample Group 16

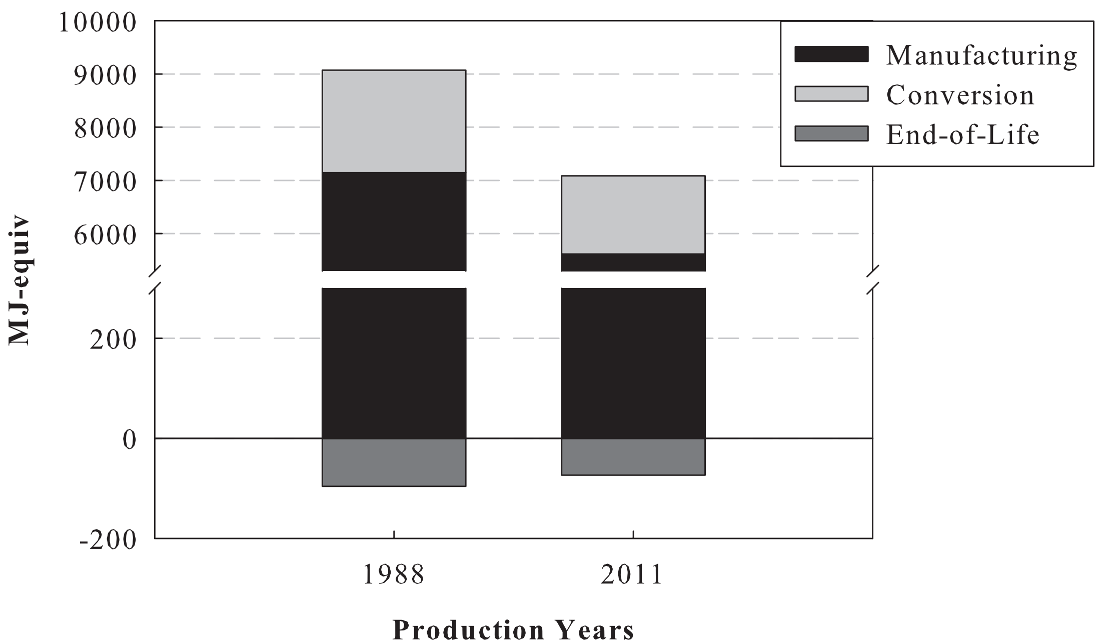

Figure A 77 Fossil fuel consumption (in MJ-equiv) of Sample Group 16

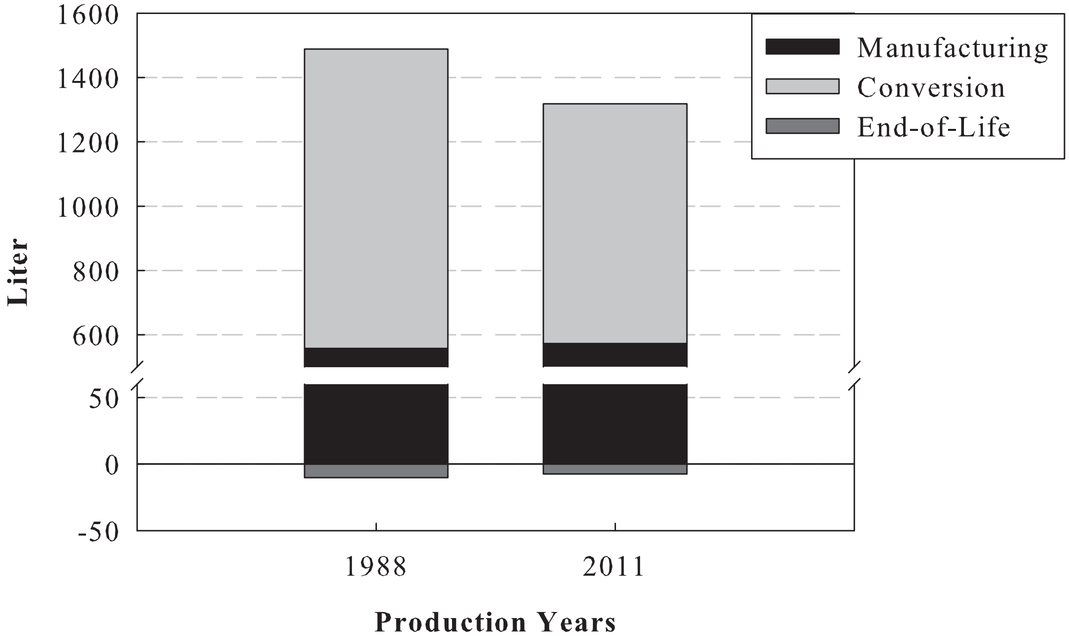

Figure A 78 Water consumption (in liter) of Sample Group 16

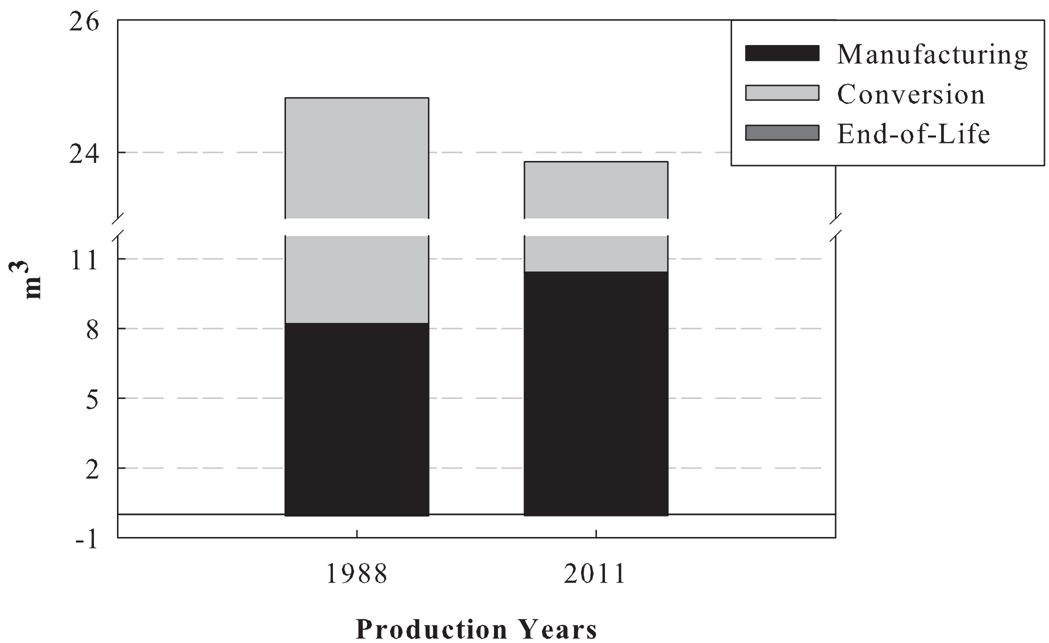

Figure A 79 Biotic resource consumption (in m^3) of Sample Group 16

Figure A 80 Mineral resource consumption (in kg) of Sample Group 16

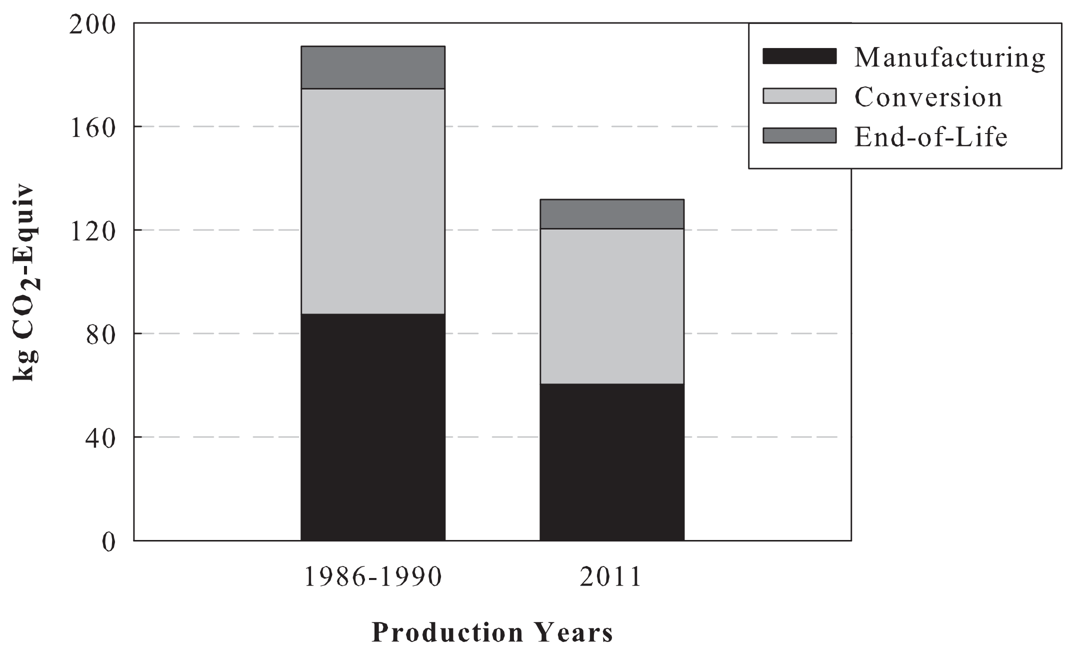

Figure A 81 Global warming potential (in kg CO_2-equiv) of Sample Group 17

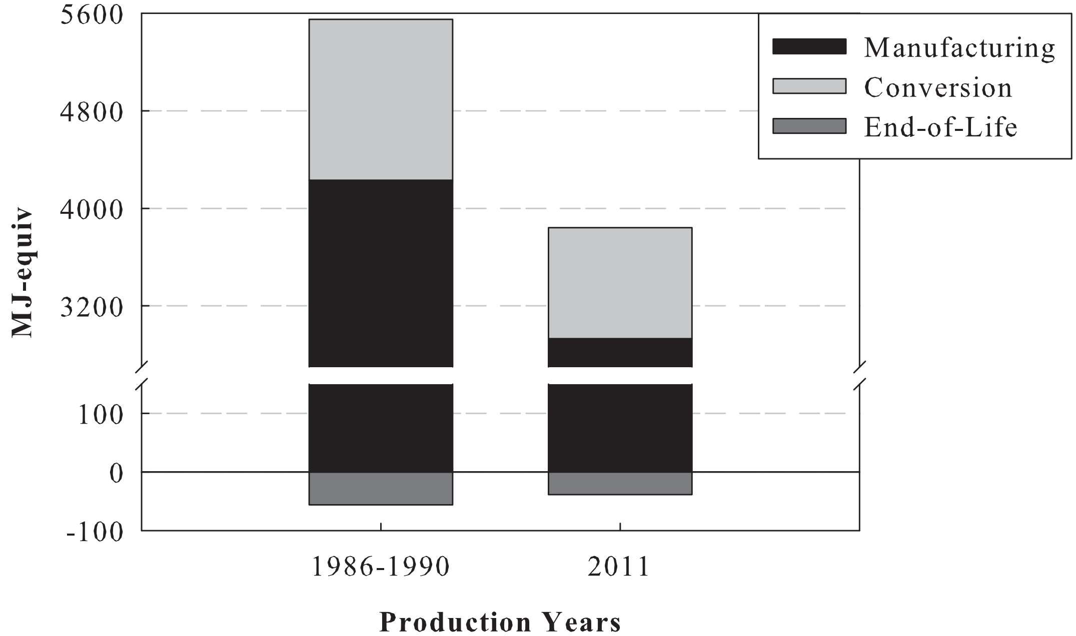

Figure A 82 Fossil fuel consumption (in MJ-equiv) of Sample Group 17

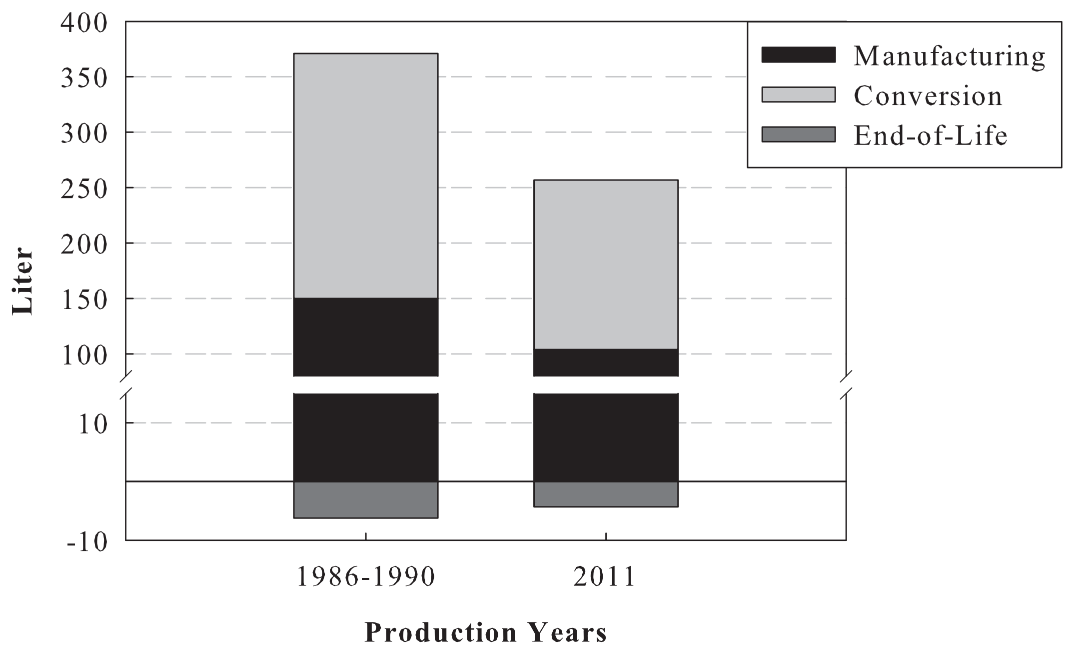

Figure A 83 Water consumption (in liter) of Sample Group 17

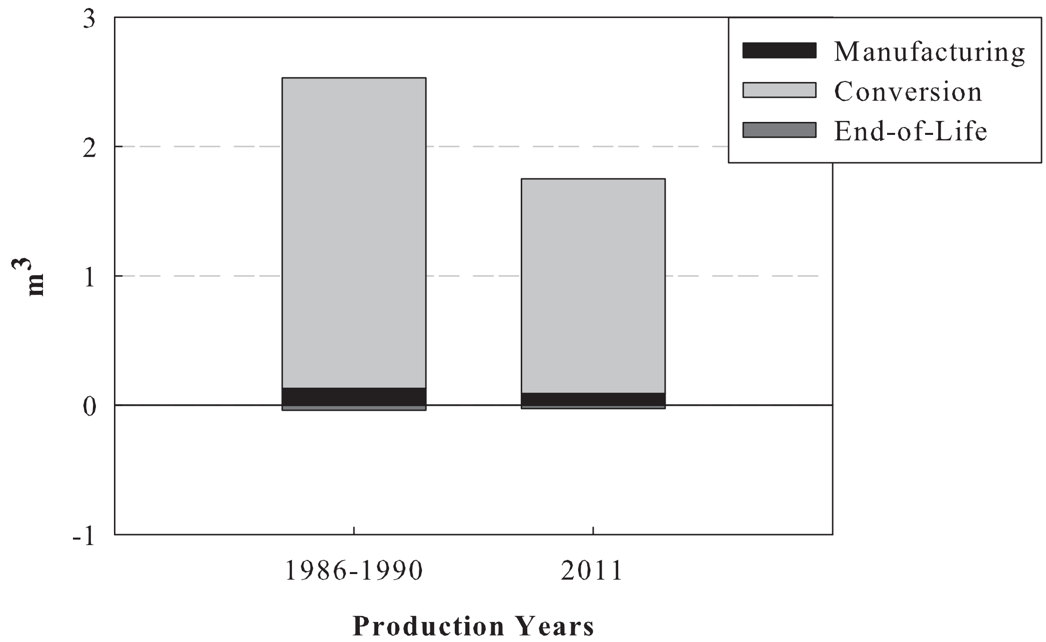

Figure A 84 Biotic resource consumption (in m^3) of Sample Group 17

Figure A 85 Mineral resource consumption (in kg) of Sample Group 17

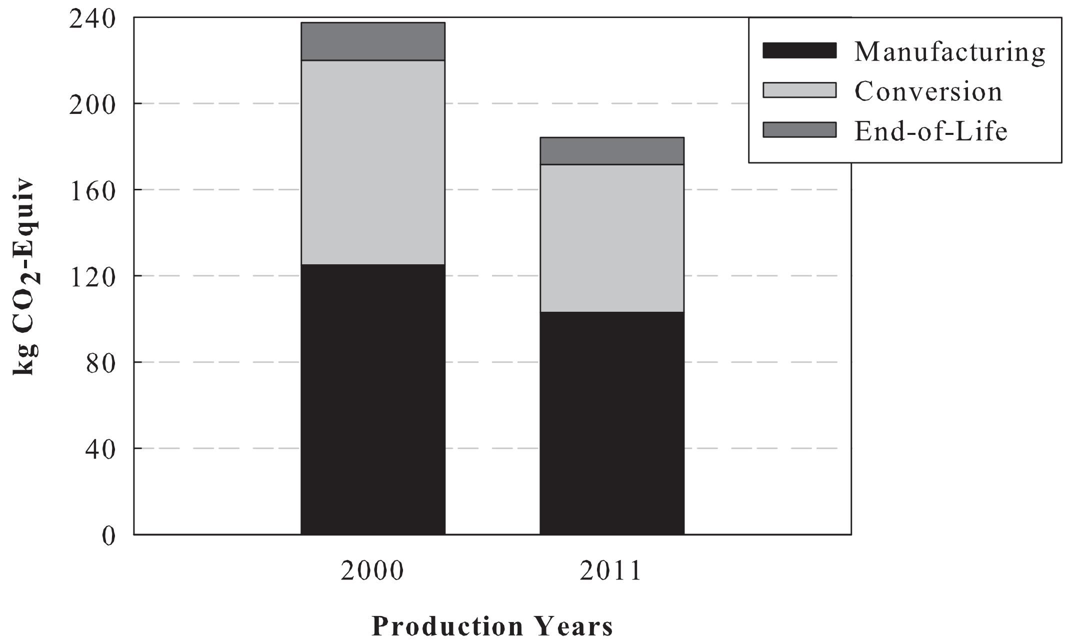

Figure A 86 Global warming potential (in kg CO_2-equiv) of Sample Group 18

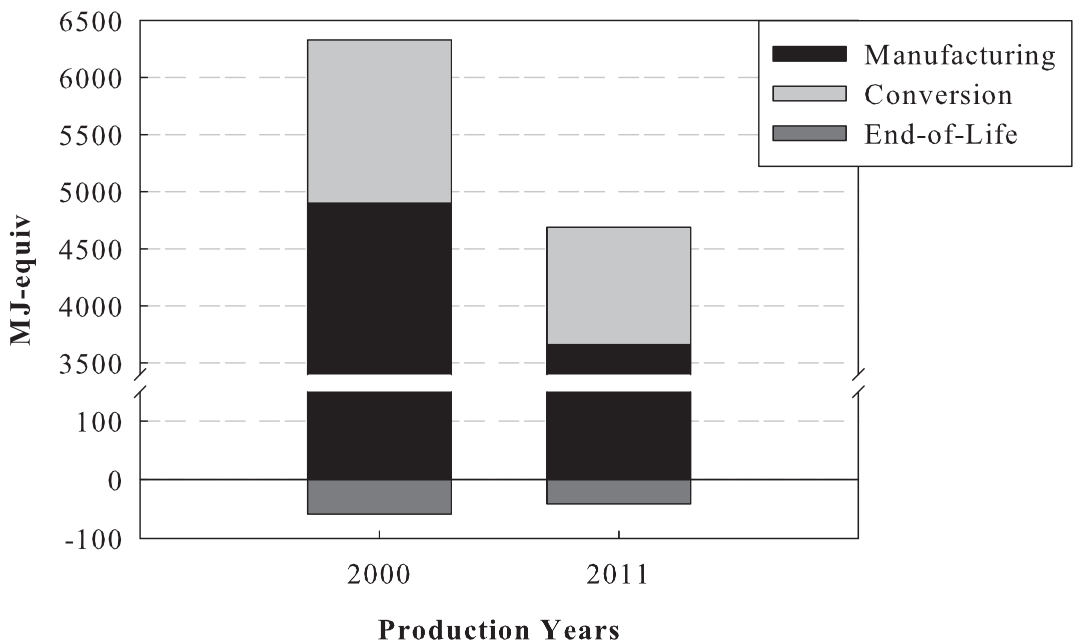

Figure A 87 Fossil fuel consumption (in MJ-equiv) of Sample Group 18

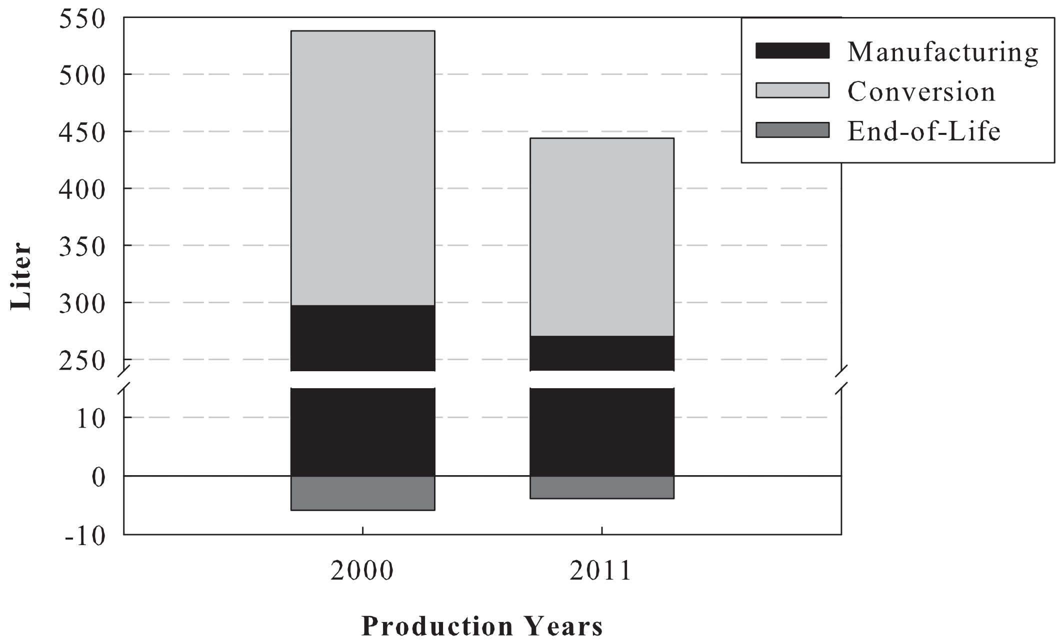

Figure A 88 Water consumption (in liter) of Sample Group 18

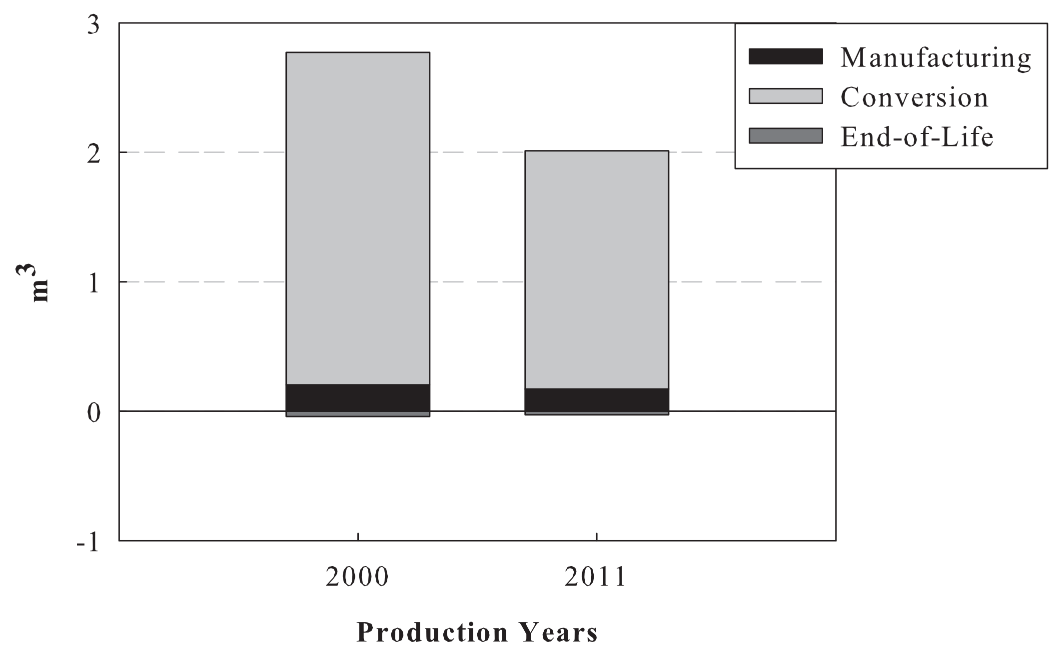

Figure A 89 Biotic resource consumption (in m^3) of Sample Group 18

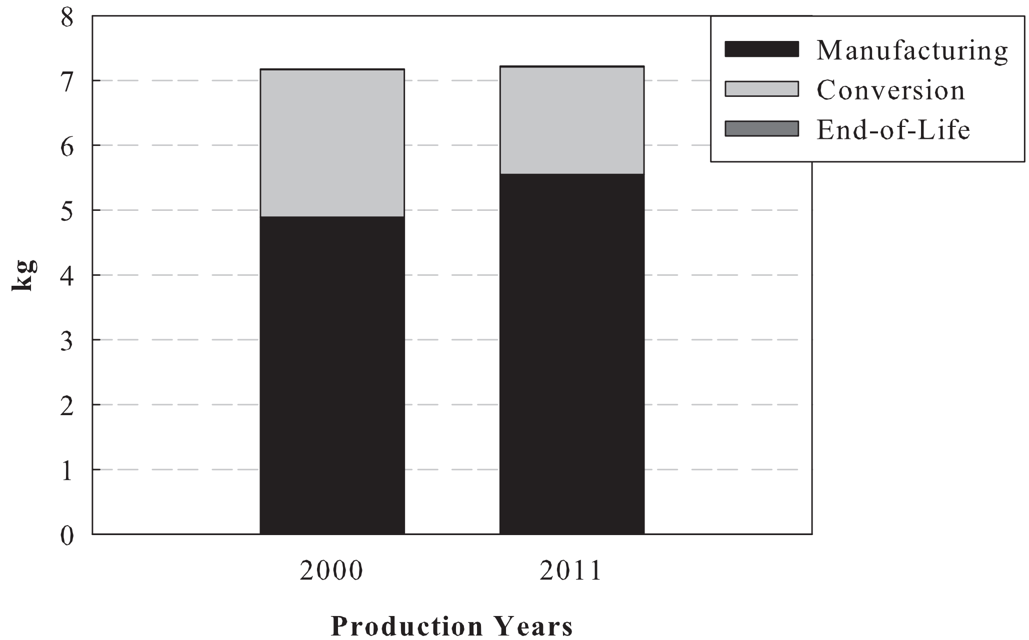

Figure A 90 Mineral resource consumption (in kg) of Sample Group 18

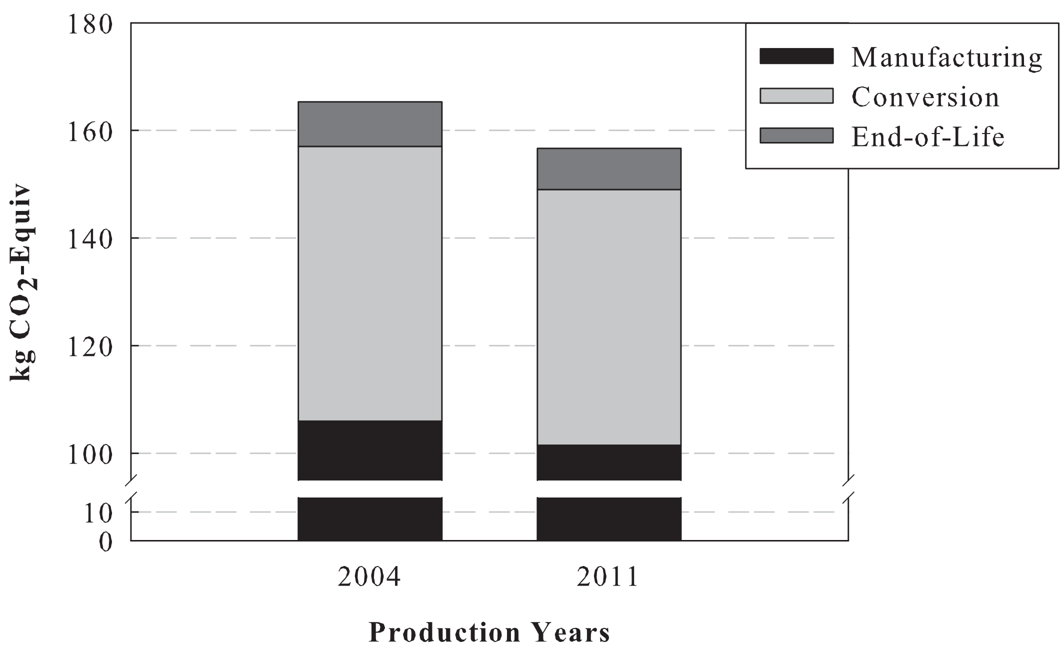

Figure A 91 Global warming potential (in kg CO_2-equiv) of Sample Group 19

Figure A 92 Fossil fuel consumption (in MJ-equiv) of Sample Group 19

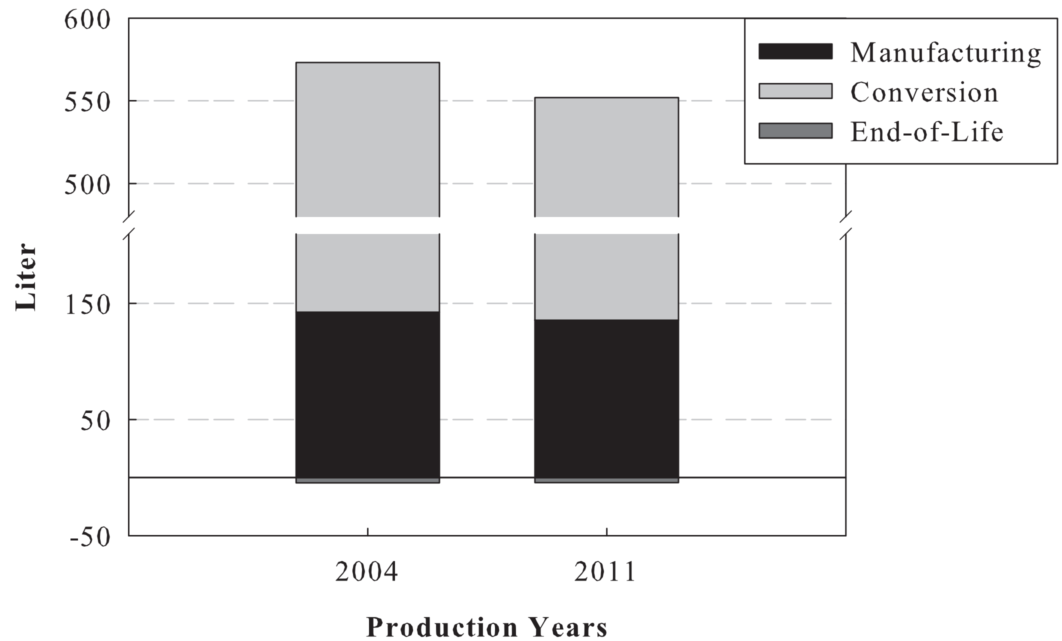

Figure A 93 Water consumption (in liter) of Sample Group 19

Figure A 94 Biotic resource consumption (in m^3) of Sample Group 19

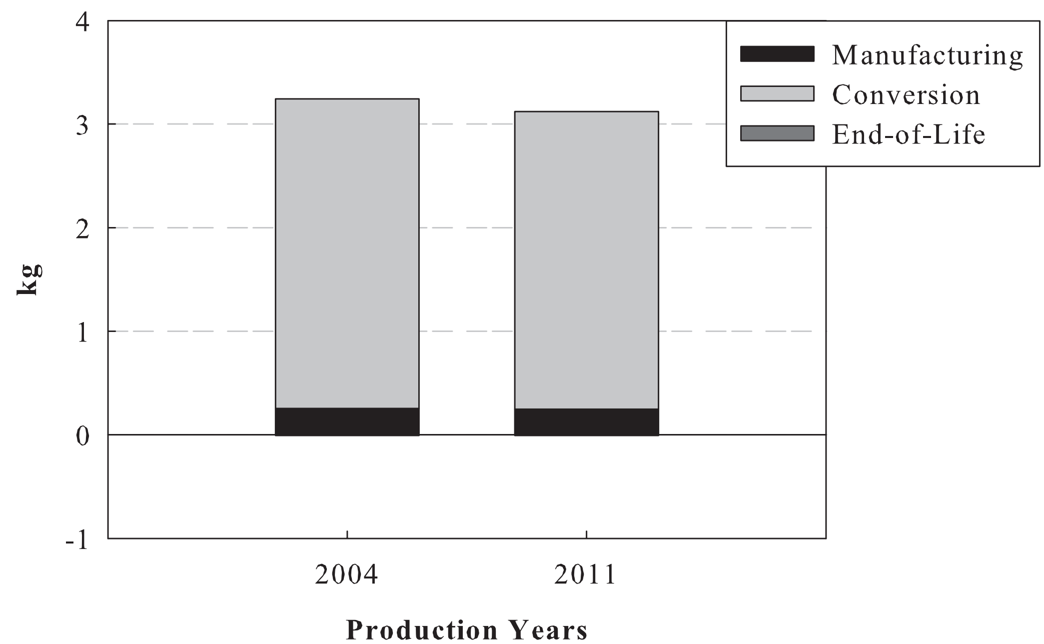

Figure A 95 Mineral resource consumption (in kg) of Sample Group 19

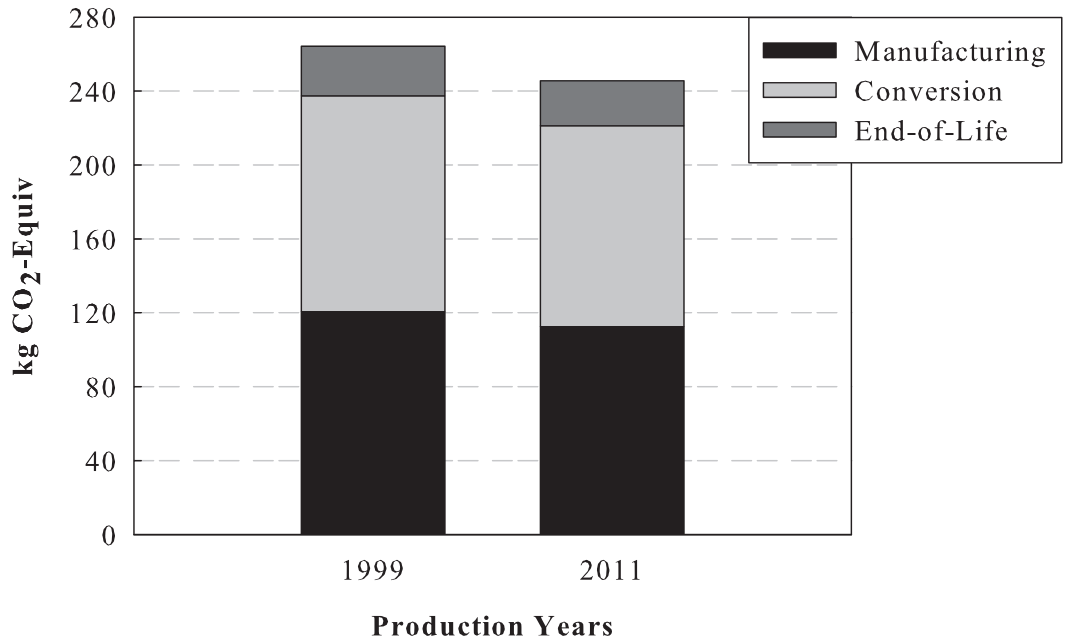

Figure A 96 Global warming potential (in kg CO_2-equiv) of Sample Group 20

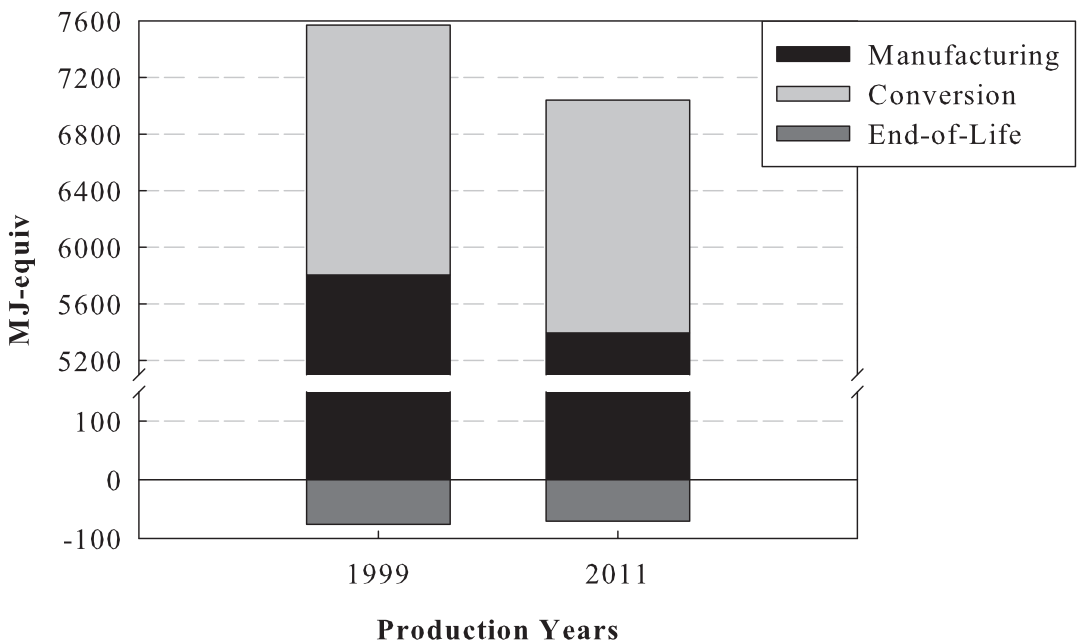

Figure A 97 Fossil fuel consumption (in MJ-equiv) of Sample Group 20

Figure A 98 Water consumption (in liter) of Sample Group 20

Figure A 99 Biotic resource consumption (in m^3) of Sample Group 20

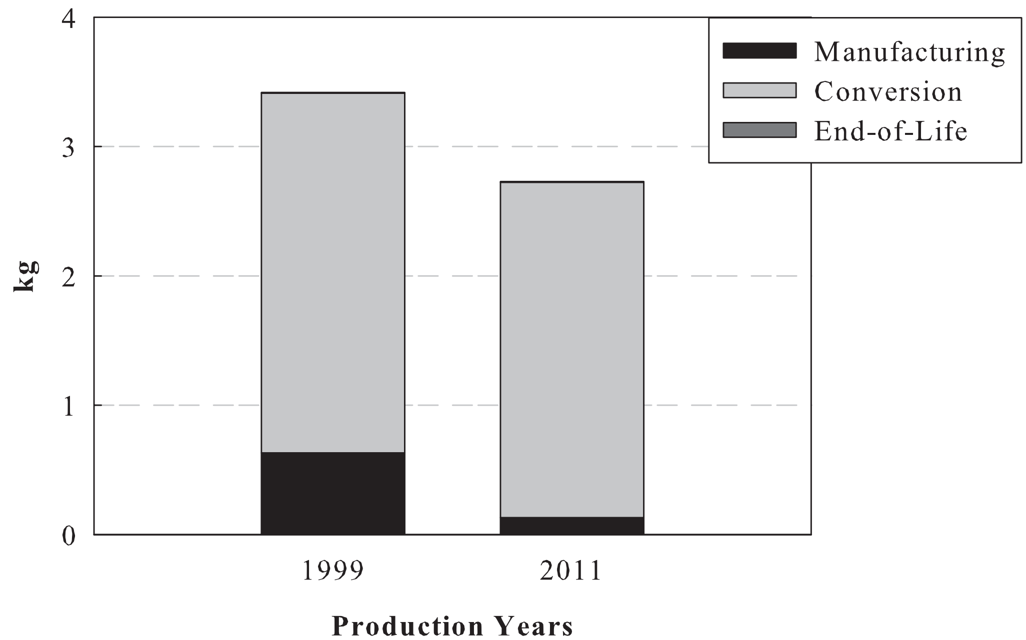

Figure A 100 Mineral resource consumption (in kg) of Sample Group 20

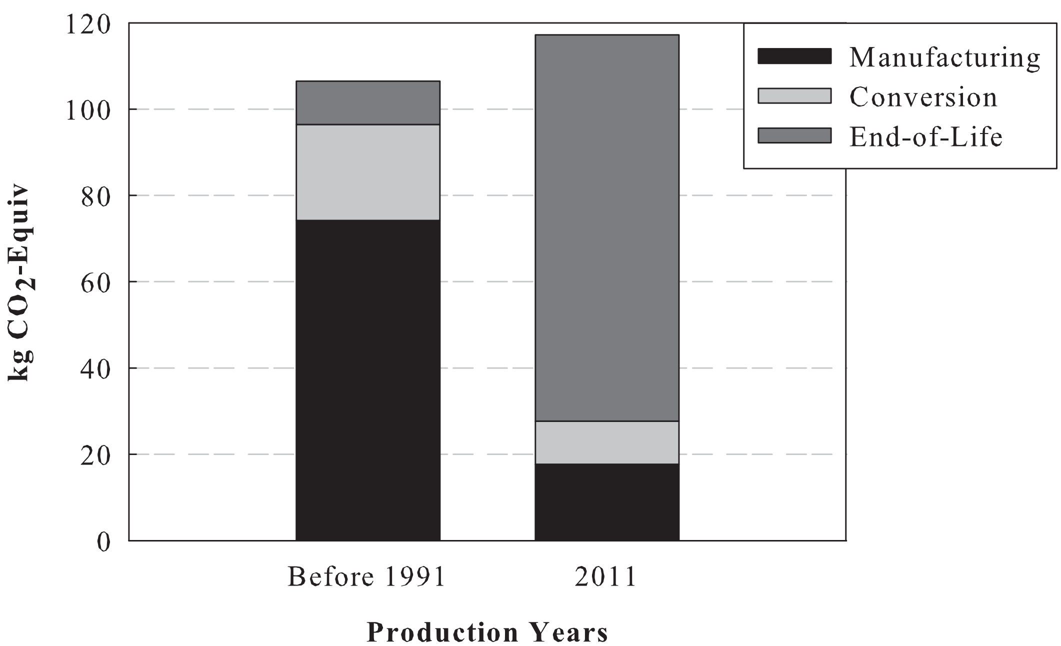

Figure A 101 Global warming potential (in kg CO_2-equiv) of Sample Group 21

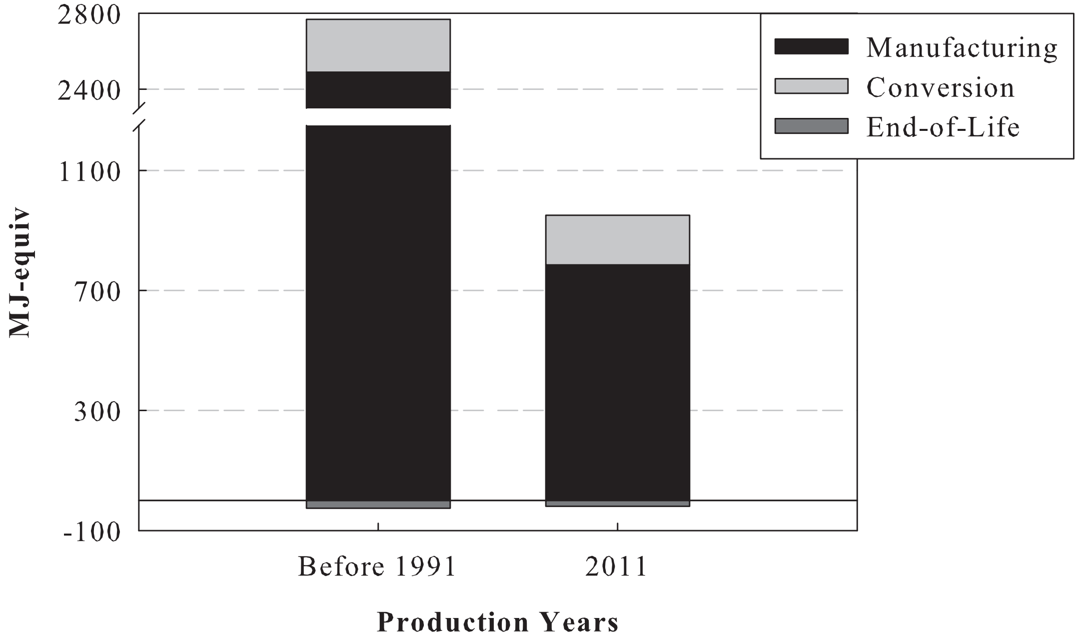

Figure A 102 Fossil fuel consumption (in MJ-equiv) of Sample Group 21

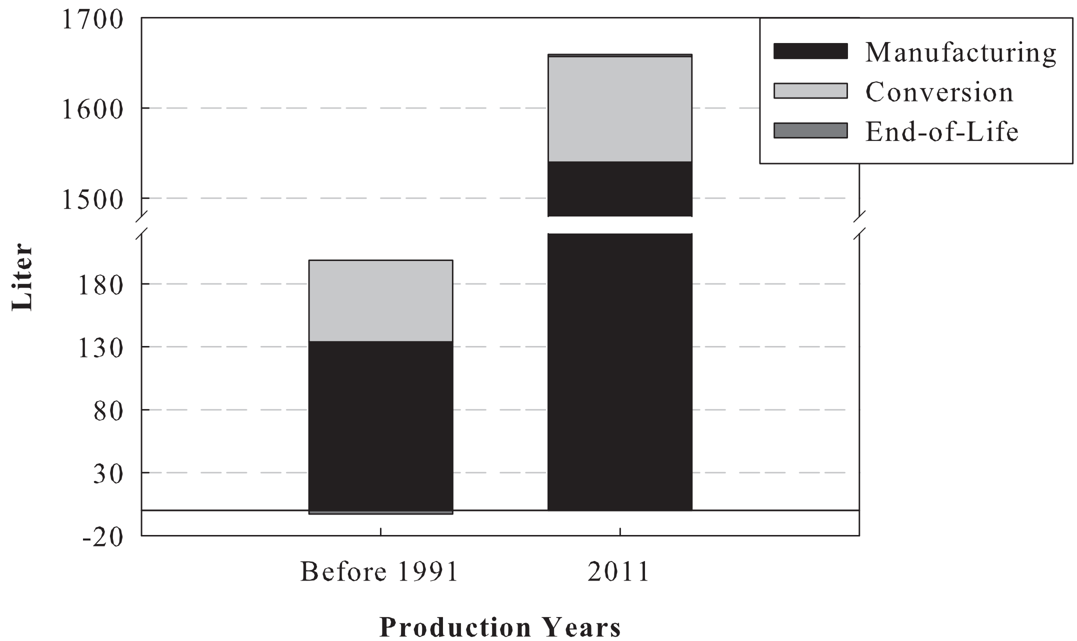

Figure A 103 Water consumption (in liter) of Sample Group 21

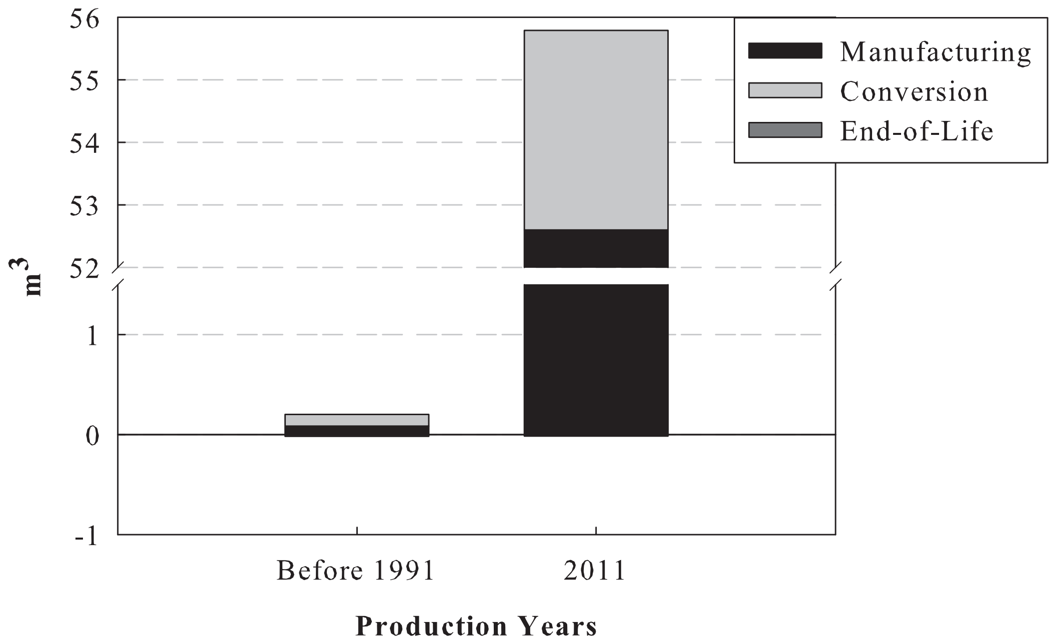

Figure A 104 Biotic resource consumption (in m^3) of Sample Group 22

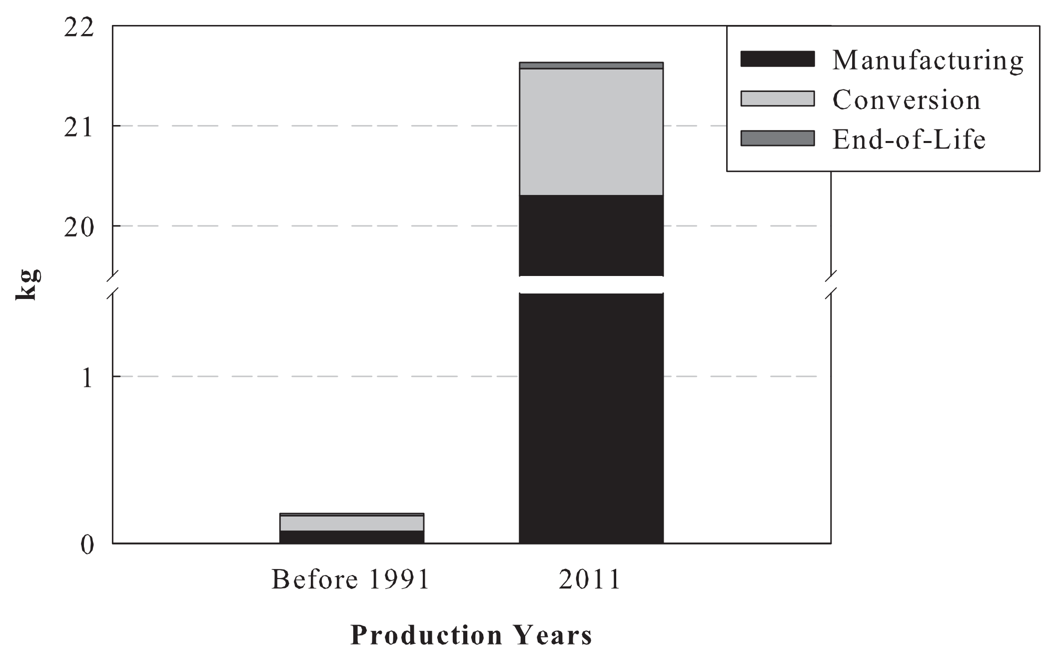

Figure A 105 Mineral resource consumption (in kg) of Sample Group 21

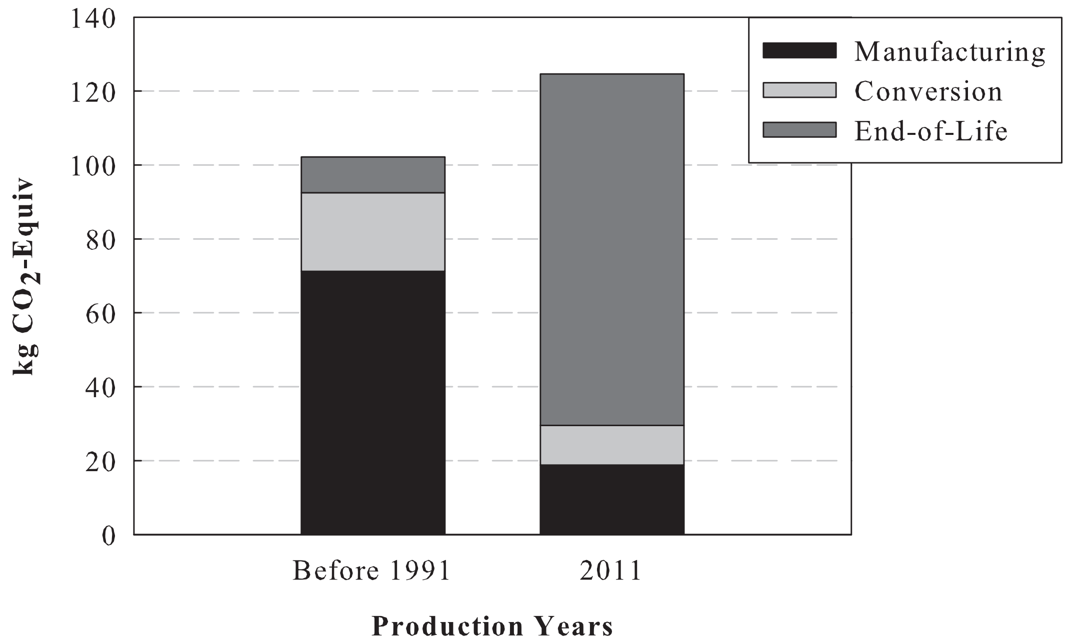

Figure A 106 Global warming potential (in kg CO_2-equiv) of Sample Group 22

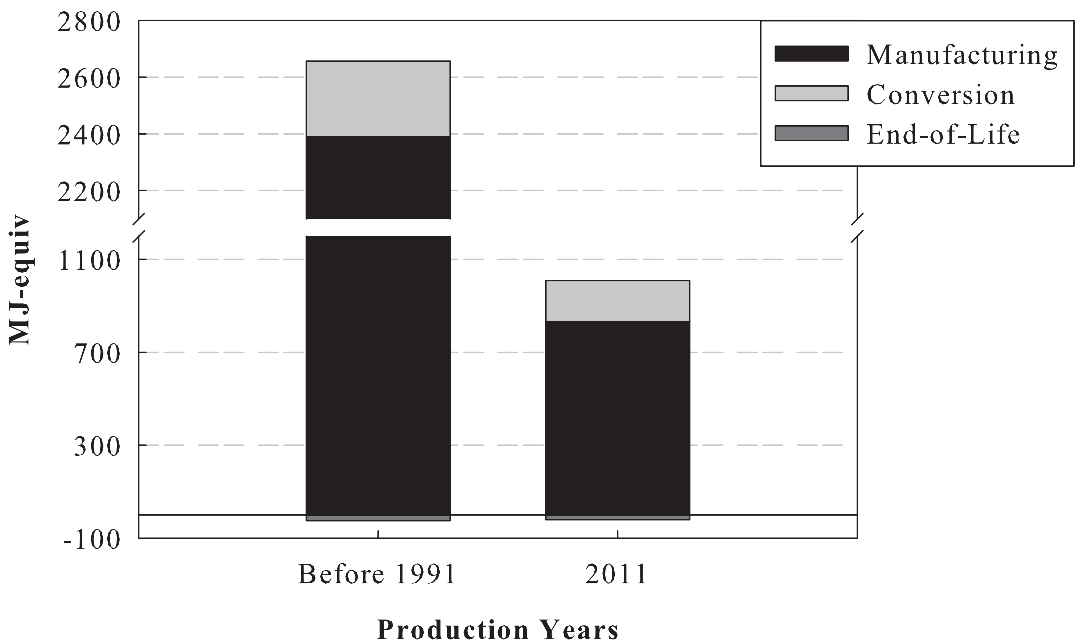

Figure A 107 Fossil fuel consumption (in MJ-equiv) of Sample Group 22

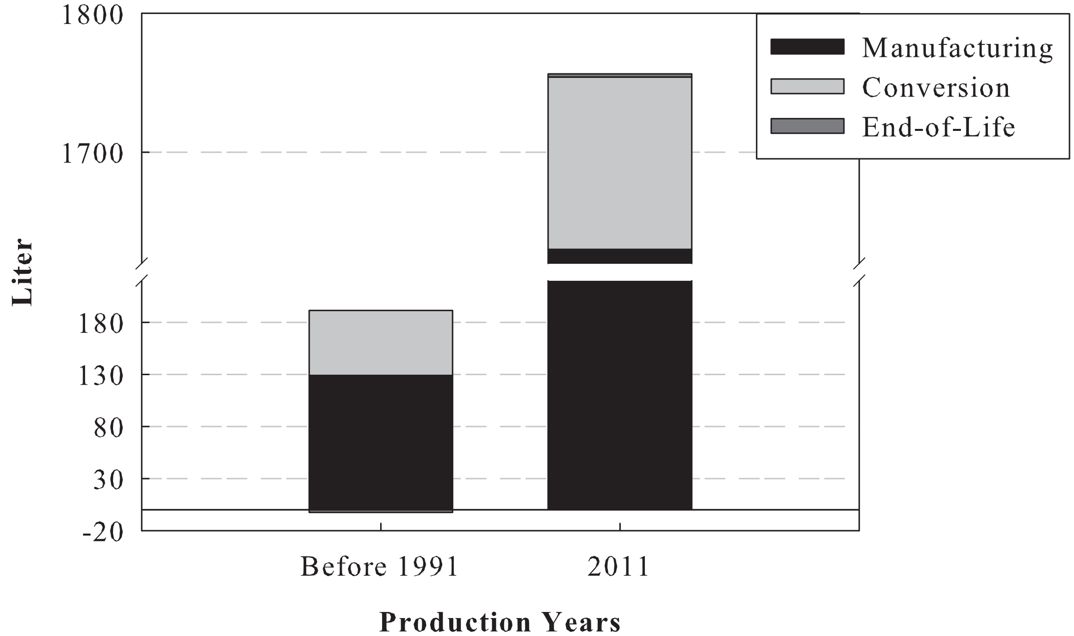

Figure A 108 Water consumption (in liter) of Sample Group 22

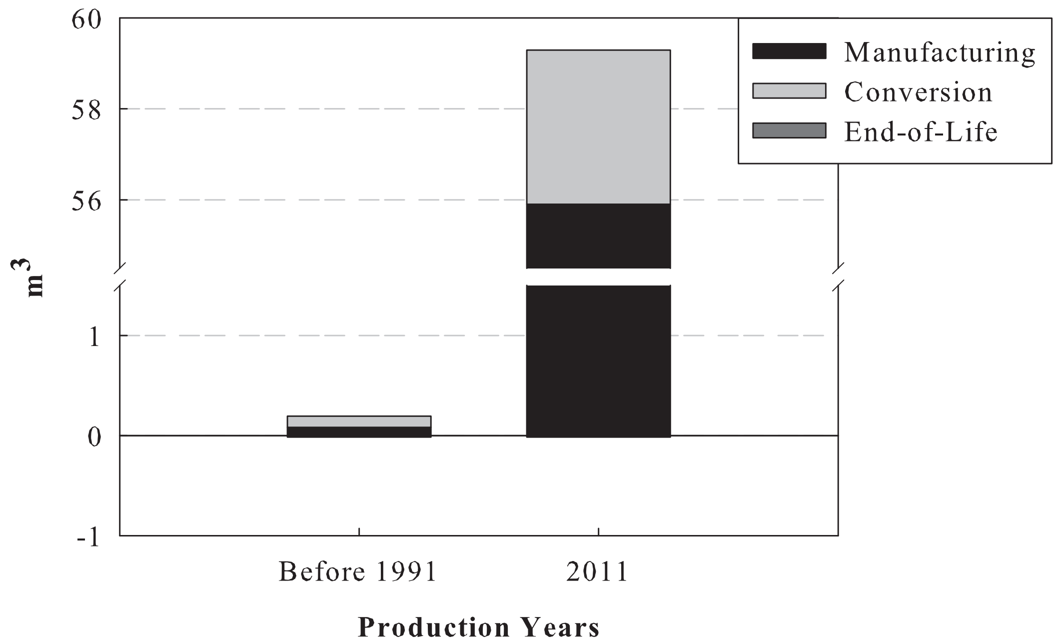

Figure A 109 Biotic resource consumption (in m^3) of Sample Group 22

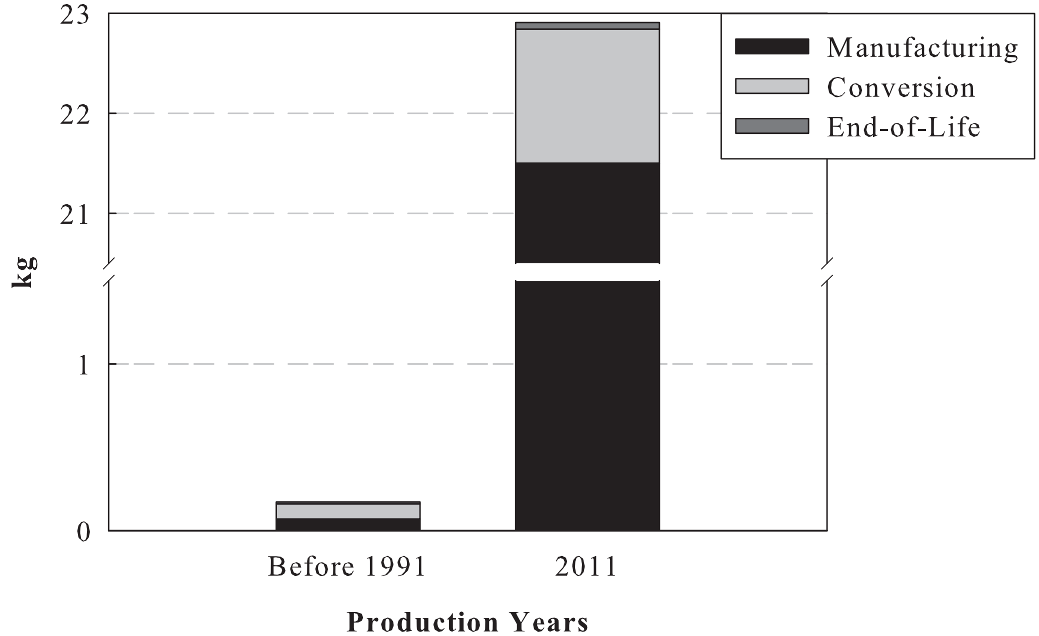

Figure A 110 Mineral resource consumption (in kg) of Sample Group 22

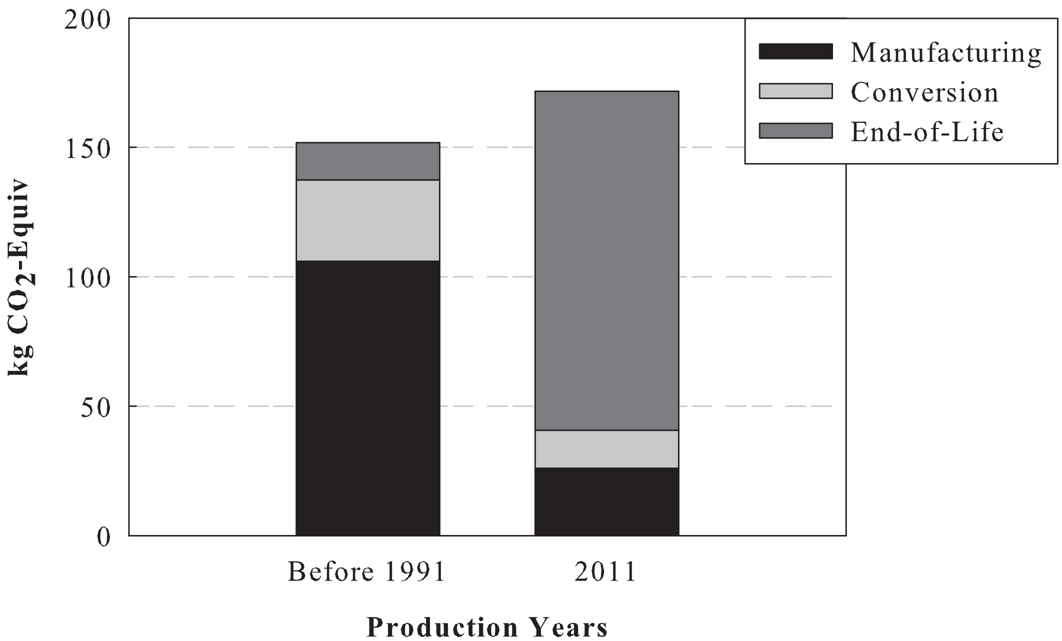

Figure A 111 Global warming potential (in kg CO_2-equiv) of Sample Group 23

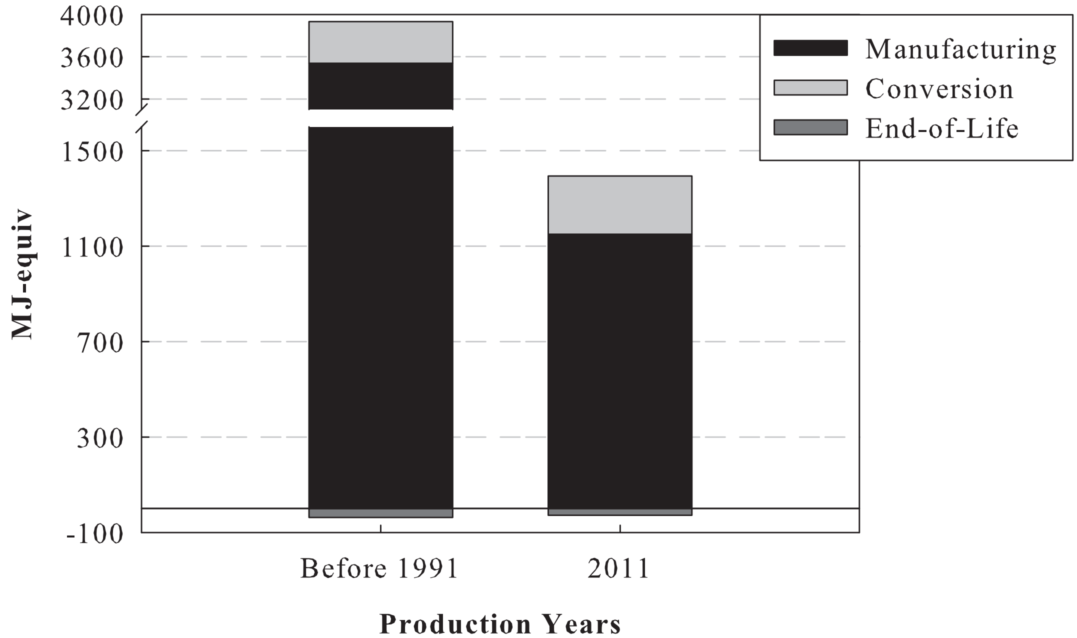

Figure A 112 Fossil fuel consumption (in MJ-equiv) of Sample Group 23

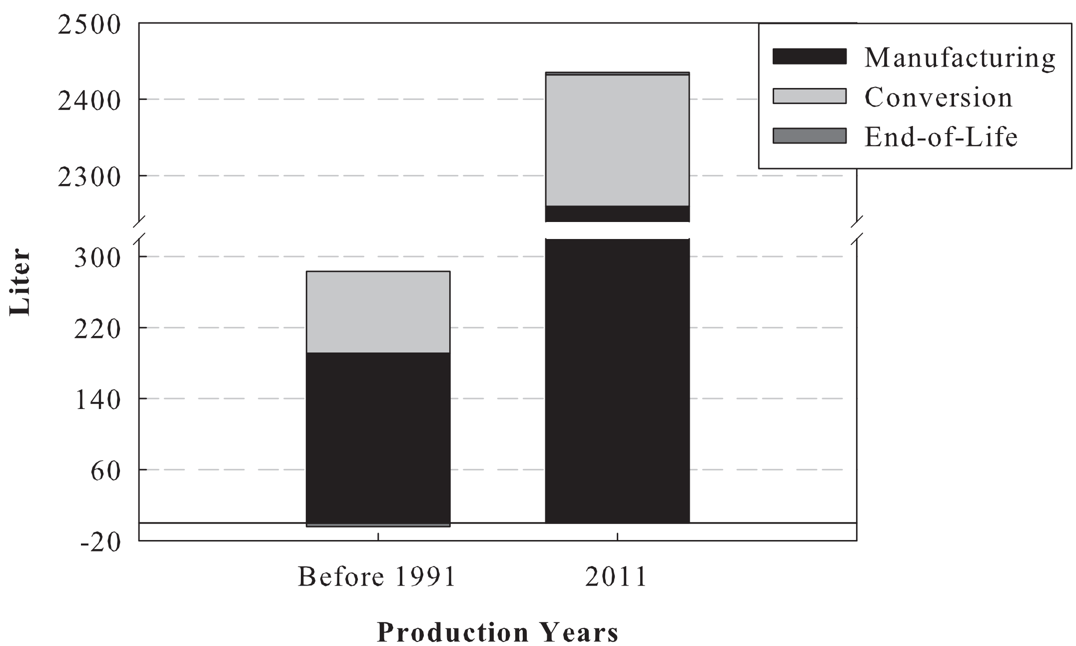

Figure A 113 Water consumption (in liter) of Sample Group 23

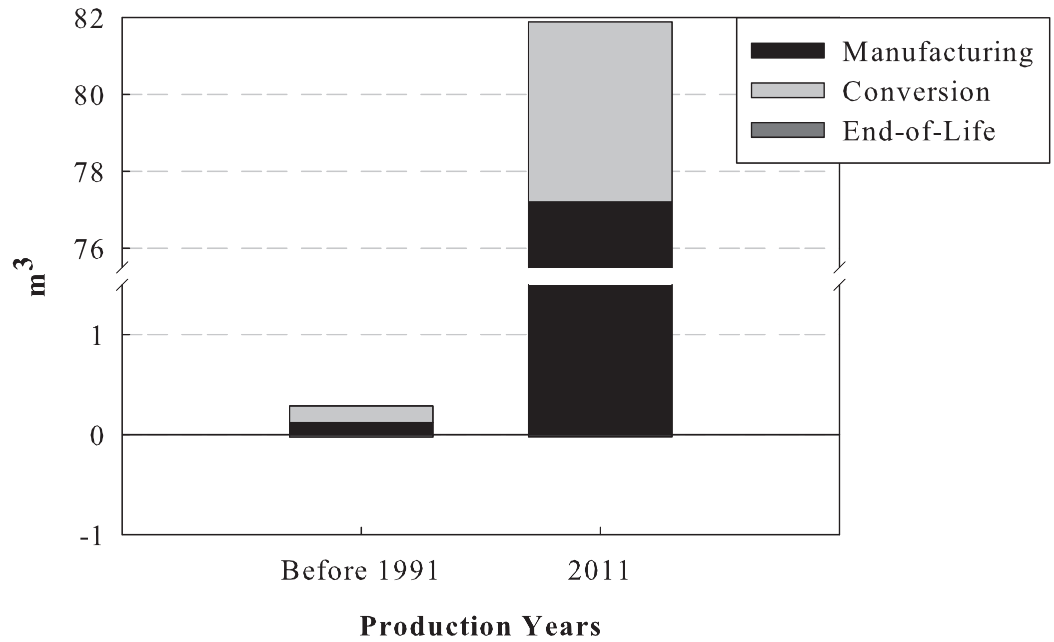

Figure A 114 Biotic resource consumption (in m^3) of Sample Group 23

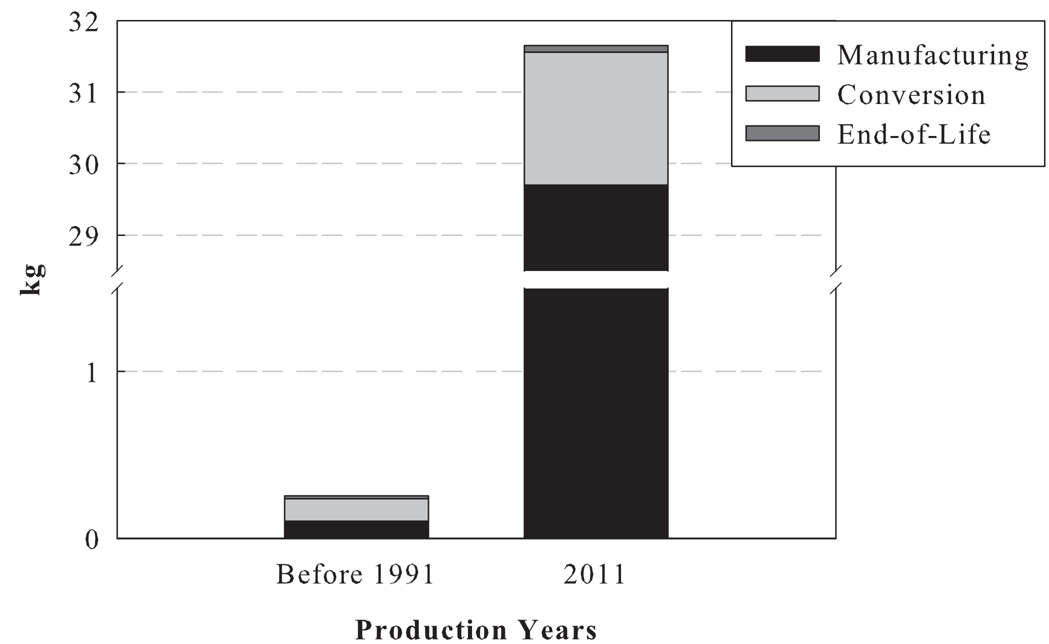

Figure A 115 Mineral resource consumption (in kg) of Sample Group 23

APPENDIX B

End-of-life percentages in COMPASS

Table A 1 End-of-life conditions for packages in COMPASS (SPC 2008).
R: Recycling, C: Composting, W: Waste to Energy, I: Incineration, L1: Landfill, L2: Litter

Material	Types	R	C	W	I	L1	L2
Solid Bleached Sulfate (SBS) Board	Folding Carton	0.273	0	0.126	0	0.601	0
	Milk Carton	0	0	0.126	0	0.874	0
	Other Paperboard Packaging	0	0	0.126	0	0.874	0
	Composite	0	0	0.126	0	0.874	0
Solid Unbleached Sulfate (SUS) Board	Folding Carton	0.273	0	0.126	0	0.601	0
	Milk Carton	0	0	0.126	0	0.874	0
	Other Paperboard Packaging	0	0	0.126	0	0.874	0
	Composite	0	0	0.126	0	0.874	0
Recycled Folding Boxboard	Folding Carton	0.273	0	0.126	0	0.601	0
	Milk Carton	0	0	0.126	0	0.874	0
	Other Paperboard Packaging	0	0	0.126	0	0.874	0
	Composite	0	0	0.126	0	0.874	0
Corrugated	Corrugated Boxes	0.736	0	0.126	0	0.138	0
	Other Paperboard Packaging	0	0	0.126	0	0.874	0
	Composite	0	0	0.126	0	0.874	0
Supercalendered Paper	Bags & Sacks	0.368	0	0.126	0	0.506	0
	Other Paper Packaging	0	0	0.126	0	0.874	0
	Composite	0	0	0.126	0	0.874	0

Table A 1 (Cont'd).

Material	Types	R	C	W	I	L1	L2
Unbleached Kraft Paper	Bags & Sacks	0.368	0	0.126	0	0.506	0
	Other Paper Packaging	0	0	0.126	0	0.874	0
	Composite	0	0	0.126	0	0.874	0
Bleached Kraft Paper	Bags & Sacks	0.368	0	0.126	0	0.506	0
	Other Paper Packaging	0	0	0.126	0	0.874	0
	Composite	0	0	0.126	0	0.874	0
Liquid Packaging Board	n/a	0	0	0.126	0	0.874	0
Modified Starch - Mater-bi	n/a	0	0	0.126	0	0.874	0
Container Glass	Beer and Soft Drink Bottles	0.345	0	0.126	0	0.529	0
	Wine and Liquor Bottles	0.15	0	0.126	0	0.724	0
	Food and Other Bottles & Jars	0.148	0	0.126	0	0.726	0
	Other Glass Packaging	0	0	0.126	0	0.874	0
	Composite	0	0	0.126	0	0.874	0
Aluminum	Beer and Soft Drink Cans	0.486	0	0	0	0.514	0
	Other Cans	0	0	0	0	1	0
	Foil and Closures	0.098	0	0.126	0	0.776	0
	Other Aluminum Packaging	0	0	0.126	0	0.874	0
	Composite	0	0	0.126	0	0.874	0
Steel	Beer and Soft Drink Cans	0	0	0	0	1	0
	Food and Other Cans	0.643	0	0	0	0.357	0
	Other Steel Packaging	0.667	0	0	0	0.333	0
	Composite	0	0	0.126	0	0.874	0

Table A 1 (Cont'd).

Material	Types	R	C	W	I	L1	L2
High-Density Polyethylene (HDPE)	Milk & Water Bottles	0.28	0	0.126	0	0.594	0
	Other Plastic Containers	0.17	0	0.126	0	0.704	0
	Bags, Sacks & Wraps	0.119	0	0.126	0	0.755	0
	Other Plastic Packaging	0.023	0	0.126	0	0.851	0
	Composite	0	0	0.126	0	0.874	0
Low-Density Polyethylene (LDPE)	Other Plastic Containers	0	0	0.126	0	0.874	0
	Bags, Sacks & Wraps	0.124	0	0.126	0	0.75	0
	Other Plastic Packaging	0	0	0.126	0	0.874	0
	Composite	0	0	0.126	0	0.874	0
Linear Low-Density Polyethylene (LLDPE)	Other Plastic Containers	0	0	0.126	0	0.874	0
	Bags, Sacks & Wraps	0.124	0	0.126	0	0.75	0
	Other Plastic Packaging	0	0	0.126	0	0.874	0
	Composite	0	0	0.126	0	0.874	0
Polyethylene Terephthalate (PET)	Soft Drink Bottles	0.366	0	0.126	0	0.508	0
	Other Plastic Containers	0.156	0	0.126	0	0.718	0
	Bags, Sacks & Wraps	0	0	0.126	0	0.874	0
	Other Plastic Packaging	0.182	0	0.126	0	0.692	0
	Composite	0	0	0.126	0	0.874	0
Polypropylene (PP)	Other Plastic Containers	0.024	0	0.126	0	0.85	0
	Bags, Sacks & Wraps	0	0	0.126	0	0.874	0
	Other Plastic Packaging	0	0	0.126	0	0.874	0
	Composite	0	0	0.126	0	0.874	0
Polystyrene (PS)	Other Plastic Containers	0	0	0.126	0	0.874	0
	Bags, Sacks & Wraps	0	0	0.126	0	0.874	0
	Other Plastic Packaging	0.067	0	0.126	0	0.807	0
	Composite	0	0	0.126	0	0.874	0

Table A 1 (Cont'd).

Material	Types	R	C	W	I	L1	L2
Expanded Polystyrene (EPS)	n/a	0	0	0.126	0	0.874	0
Polyvinyl Chloride (PVC)	Other Plastic Containers	0	0	0.126	0	0.874	0
	Bags, Sacks & Wraps	0	0	0.126	0	0.874	0
	Other Plastic Packaging	0	0	0.126	0	0.874	0
	Composite	0	0	0.126	0	0.874	0
Polyvinylidene Chloride (PVDC)	n/a	0	0	0.126	0	0.874	0
Polylactic Acid Pellet (PLA)	Bottles	0	0	0.126	0	0.874	0
	Other Plastic Containers	0	0	0.126	0	0.874	0
	Bags, Sacks & Wraps	0	0	0.126	0	0.874	0
	Other Plastic Packaging	0	0	0.126	0	0.874	0
	Composite	0	0	0.126	0	0.874	0
Ethyl Vinyl Acetate (EVA)	n/a	0	0	0.126	0	0.874	0
Nylon 6	n/a	0	0	0.126	0	0.874	0
Polycarbonate	n/a	0	0	0.126	0	0.874	0

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