2005

INNOVATIVE PRODUCT DESIGN FOR SUSTAINABILITY ENHANCEMENT IN ALUMINUM BEVERAGE CANS BASED ON DESIGN FOR SUSTAINABILITY CONCEPTS

Jason Chun Tchen Liew
University of Kentucky

ABSTRACT OF THESIS

INNOVATIVE PRODUCT DESIGN FOR SUSTAINABILITY ENHANCEMENT IN ALUMINUM BEVERAGE CANS BASED ON DESIGN FOR SUSTAINABILITY CONCEPTS

A new methodology for innovative product development based on the application of sustainability principles for the entire life-cycle of a product and beyond is developed. This involves an analysis of multi-life cycle material flow leading towards "perpetual life products", making it truly sustainable. In order to achieve the function of such a sustainable product, it has to fulfill the concept of 6R (Recover, Reuse, Recycle, Redesign, Reduce and Remanufacture), which are composed of 6 stages of material flow in a product's life, as opposed to the traditional 3R (Reduce, Reuse, Recover) concept. We apply the 6R concept in designing a new aluminum beverage can with much enhanced sustainability factors, especially in recycling processes.

KEYWORDS: Design for Sustainability, Multiple and Perpetual Product Life-cycle, 6R concept, Sustainable Product, Aluminum Beverage Can

Jason Chun Tchen Liew

6 May 2005

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THESIS

Jason Chun Tchen Liew

The Graduate School

University of Kentucky

2005

INNOVATIVE PRODUCT DESIGN FOR SUSTAINABILITY
ENHANCEMENT IN ALUMINUM BEVERAGE CANS BASED ON
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THESIS

A thesis submitted in partial fulfillment of the requirements for
the degree of Master of Science in Manufacturing Systems Engineering
in the College of Engineering at the University of Kentucky

By

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Lexington, Kentucky

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Lexington, Kentucky

2005

This work is dedicated to my parents for their unceasing support during my undergraduate and graduate studies at the University of Kentucky. Their word of encouragements is the reason that kept me dedicated to this work.

I would also like to remember a special person in my life, Chin Hui Hui for standing solidly behind me all this time. Her care and love are the reasons where I am today. Thank you.

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Introduction

1.1 Thesis Focus and Objective

Sustainable development is critical in today's world with dwindling land reserves, natural resources and growing populations which lead to increased natural resources requirements and energy consumption rates as well as, byproducts from economic developments such as environment pollutions and societal changes. Historically, the manufacturing sectors have always played an important part in any economic or societal growth. Therefore, it is imperative to have sustainable manufacture. Sustainable manufacture is composed of three sub-elements; sustainable product, sustainable manufacturing systems and sustainable manufacturing process [1].

In this thesis, efforts will be put forth to identify a new sustainable product design methodology. A new methodology for innovative product development based on the application of sustainability principles for the entire life-cycle of a product and beyond is developed. This involves an analysis of multi-life cycle material flow leading towards "perpetual life products", making it truly sustainable. In order to achieve the function of such a sustainable product, it has to fulfill the concept of 6R (Recover, Reuse, Recycle, Redesign, Reduce and Remanufacture), which are composed of 6 stages of material flow in a product's life, as opposed to the traditional 3R (Reduce, Reuse, Recycle) concept. This new product design methodology has wide ranging applications, from automobiles to consumer electronics product designs. We will apply the 6R concept to design a new aluminum beverage can with enhanced sustainability factors, especially the recyclability.

One of the major advantages of aluminum beverage can is its capability to be recycled over and over again without any quality loss, contributing to the environment by reducing the need for fresh bauxites to make primary aluminum. As with most mature and well developed products, the innovation curves tend to reach a flat line, in addition to dwindling recycling rate over the years. Therefore, it is critical to take a look at the design of the aluminum beverage can from a fresh perspective in order to come up with possible solutions to increase its sustainability, through its recyclability.

1.2 Previous Research on Sustainability

Before embarking on finding ways to enhance the sustainability of any product, we need a proper definition of sustainability, sustainable product and sustainable product design methodology. The most recognized definition of sustainability come from the Bruntland Commission as “meeting the needs of the present without compromising the ability of future generations to meet their own needs” [2]. The term sustainability contains the idea that humans on this planet should live in such a way, that the needs of the present are satisfied without risking that future generations will not be able to meet their needs, with balance between ecological, economic and social dimensions [3]. Sustainability is also defined as the tendency of ecosystems to dynamically balance their consumption patterns of matter and energy, and evolve to a point where life itself can continue

[4]. Achieving a comprehensive, global sustainability heavily depends on collective and unified efforts of the global community involving multi-disciplinary approach in three core areas of research: environment, economy and society [1]. Most research work on sustainability has so far primarily focused on environmental effects. However, to achieve comprehensive sustainable developments, it is important to look at all major influencing elements of sustainability.

Sustainable products are products that are fully compatible with nature throughout their entire life-cycle [5]. According to Sustainable Products Corporation, sustainable products provide the greatest global environment, economic and social benefits while protecting public health, welfare and environment and are measured over their entire life-cycle, from raw materials extraction to final reuse or disposal [6]. A sustainable product should make a large economic impact while making a major contribution to environment and societal needs [7].

There are several existing design methodologies to design and produce sustainable products. The first is called BioDesign using the cyclic, solar and safe elements [5], [8]. According to this approach, when activity equals damage, do not try to reduce the environmental impact by trying to reduce the amount of activity, but change the activities so that they are biocompatible and cause no damage [8]. A sustainable product should be designed with these 5 elements in mind: cyclic, solar, safe, efficient and social. Cyclic means that the product has to be made from organic materials which is recyclable or compostable, or is made from minerals that are continuously cycled in a closed loop. Solar means the product must use solar energy or other forms of renewable energy, while safe means that the product should not be toxic in manufacture, use or disposal. The element efficient simply means that the product should use 90% less material, energy and water during manufacture compared to similar products in 1990. The last element, social, means that the product's manufacture and use must support basic human rights and natural justice.

Design for Environment (DFE) methodology considers product development as an integrated system where every decision influences the whole process and results in different impacts on the environment [4]. DFE utilizes technological innovations and methodological proceedings to help designers and decision makers to produce goods and services that are economically viable and ecologically friendly [4]. First, the detailing of product needs and characteristics is done to identify the environmental aspects that can make the product greener. Next, an environmental impact analysis is done on the data collected from the first stage. Lastly, low cost, design innovation and eco-friendly improvements are made to the product from the results of the environmental impact analysis.

Products, processes and practices can be designed with a specific sustainable growth rate for the control of pollution and for the reduction of material and energy use by adopting the Paradigm E concept. Any corporation that adopts the Paradigm E must emphasize Ecology, Environment, Energy, Economy, Empowering, Education and Excellence in all product life-cycle decisions [9]. The true goals of design for sustainability under the Paradigm E are material and energy resource consumption, waste reduction, and prevention of pollution because by pursuing these goals, green and robust products and processes are produced [9].

The Sustainable Product Design (SPD) concept shows that it is fruitless to try to define what sustainable product design is, because SPD encompasses a great diversity of approaches which will vary with place, time, environment, culture and knowledge [10]. Designing a sustainable product usually needs to incorporate several factors, first being that necessity will dictate inventiveness. Sustainability demands resourcefulness and new solutions have to be found which require less energy and costs [10]. Secondly, designers need to improvise and be spontaneous with working with the constraints of resources and realize that most products are actually a physical manifestation of unsustainable practices [10]. This may include using too many moving parts in a product, which lowers its reliability or not utilizing the latest technology such as CAD and FEM analysis in the design stage. A sustainable product also needs to have aesthetic longevity and efficient energy use. In addition, it has to be able to be manufactured locally to contribute to the economy and if it is to be mass produced, integration of locally made components is necessary. All of these factors can be broadly categorized into four core elements; Economics, Environment, Ethics and Social [10].

Another approach to sustainable product design with emphasis on sustainable manufacture and environmental requirements is shown in Figure 1.1 [11]. According to this, there are four examples of methodologies that have recently been developed and represent the most significant stages of a product's life-cycle, which have an influence on its environmental performance. They are introducing environmental awareness to customer requirements (CR), assessing environmental performance as a design objective, performing life-cycle assessment (LCA) during the design process and evaluating the product's potential for reuse and recycling. Factoring in the environmental requirements, a new sustainable approach to product development and usage in four stages of the product's life-cycle is derived. They are environmentally conscious quality function deployment (ECQFD), sustainable trade-off model for design, life-cycle assessment and end-of-life options (EOL).

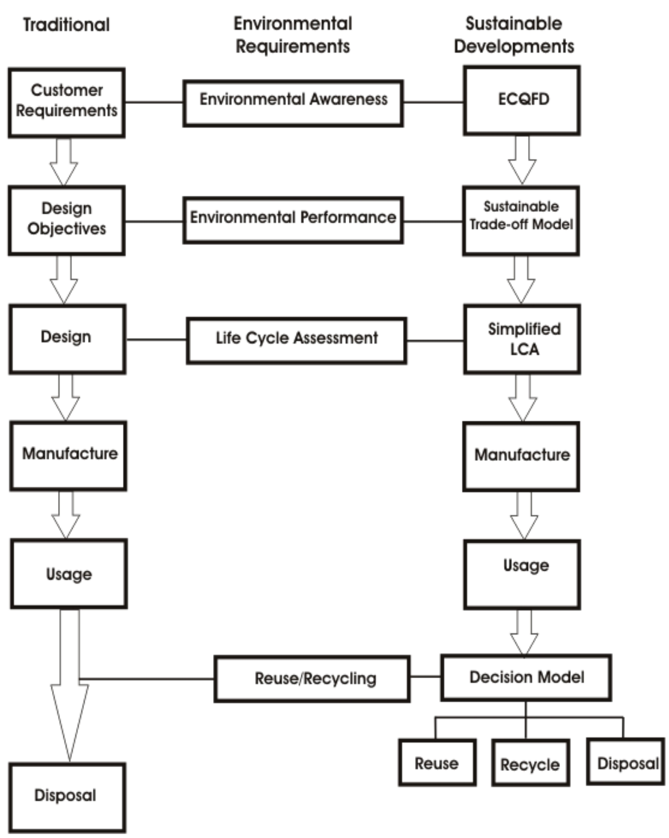

Figure 1.1: Methodologies for Sustainable Manufacturing at Stages of Product Life-Cycles [11].

One of the roles of a sustainable product is to reduce or moderate unintended pollutions. Therefore, a sustainable product design methodology should take into account how to reduce pollutions through sustainable product design [12]. There is three ascending sustainable product design scenarios, with the first being Eco-redesigns (E-), which is a short-term, low-functional-change, low-risk approaches that involve modifying present product designs, manufacturing systems, materials and distribution systems and resulting in low degree of environmental improvements [12]. The second scenario is Eco-innovations (E+), which are long term, high-functional-change group of approaches that focus on reinventing the ways and means used to provide benefits to customers through products [12]. Lastly, emerging/unproven and radical technology may be built into the product through Sustainable Technology innovations (E++), with the objective of introducing the highest degree of potential environment improvements.

Most methodology for designing a sustainable product assumes the product as having only a single life-cycle. This is a severe limitation, because a sustainable product needs to have a “closed-loop” material cycle. This idea can even be taken further by saying that a truly sustainable product design methodology is a fusion of all traditional product design methodologies with emphasis on all three pillars of sustainability, environment, economy and society, that produces a sustainable product with multiple and perpetual life-cycle. In addition, most sustainable product methodologies emphasize the systems perspectives. This is a top down approach as opposed to the bottom up approach when working on sustainability from the product level. There are many advantages to enhancing sustainability of a product from the product point of view which will be discussed in later chapters.

Chapter Two

Introduction to Packaging and Aluminum Beverage Cans

Throughout the history of mankind, we have always been known as explorers and inventors. Along with the discovery of fire and invention of the wheel, the knowledge of packing food to extend its life is ranked as one of the most important milestones in the human history that has often been overlooked. The technology of food packaging has been the catalyst that propels man to explore the new world and discover new things. It also helped to maintain the civilization by supplying people with indispensable fresh food.

Over the years, the technology of food packaging keeps developing, with new materials being used to construct the containers to keep food in, chemicals to preserve food, and new manufacturing technology to package food. Nowadays, aluminum is one of the most important materials in the food packaging industry; it is being used widely to make foils, containers, bottles and cans. In this section, we will look closely at the role aluminum plays in revolutionizing food packaging, and the development of aluminum beverage cans.

2.1 Aluminum in Packaging

In 1795, the government of Napoleon offered a 12,000 francs reward to anyone who came up with a method of preserving food. Fourteen years later, in 1809, Nicolas Appert, known as the father of canning, managed to preserve food by sterilizing it, and he was awarded the 12,000 francs. The first food container was patented by Peter Durand of England in 1810. It was made out of tin-plated iron. In 1818 he introduced his container to America. One year later, in 1819, Thomas Kensett Sr. and Ezra Daggett started to can oysters, fruits, meats and vegetables in New York. Kensett eventually patented the tin-plated can in 1825. Over the years, steel, plastics, glass and aluminum have been used to make food containers, which evolved into many different shapes and sizes to cater to the changing needs of consumers. Fast-forward to the twenty-first century; aluminum has emerged as an important player in the food packaging industry due to its superiority. Aluminum is known as a long life packaging material for perishable food.

Early food packaging needed only to satisfy the most basic requirement of the time, keeping food fresh and portable. However nowadays, besides its protective properties, packaging has to fulfill economical, technical, social and ecological demands [13]. The use of aluminum in the food packaging industry started in 1910, when the first aluminum foil was produced. Aluminum was rolled into sheets with thickness of just a hundredth of a millimeter. These sheets were then laminated with paper to produce aluminum foil. The following year, in 1911, chocolate manufacturers started to use aluminum foil to wrap their chocolates. Eventually, aluminum foil displaced the use of tin foil. From then on, aluminum use in the packaging industry has continued to expand, as shown in Figure 2.1.

Today, aluminum is widely used and is dominant in the packaging industry (Figure 2.2). Aluminum packaging offers a range of properties that contribute to a high degree of acceptance with traders and consumers alike [13]. Aluminum packaging is lightweight; the metal itself is easily formed, and provides good shape stability. It also has good thermal conductivity, and reflects light and UV rays. Its excellent barrier properties protect contents in the aluminum package, and its corrosion resistance makes it invincible for many types of food and beverage. Aluminum is also chemically neutral, and packaging made out of it can be printed on easily. Most important from the viewpoint of sustainability is its ability to be recycled over and over again, as we shall discuss in later chapters. Physiologically, aluminum is harmless. All the attributes are listed in Figure 2.3.

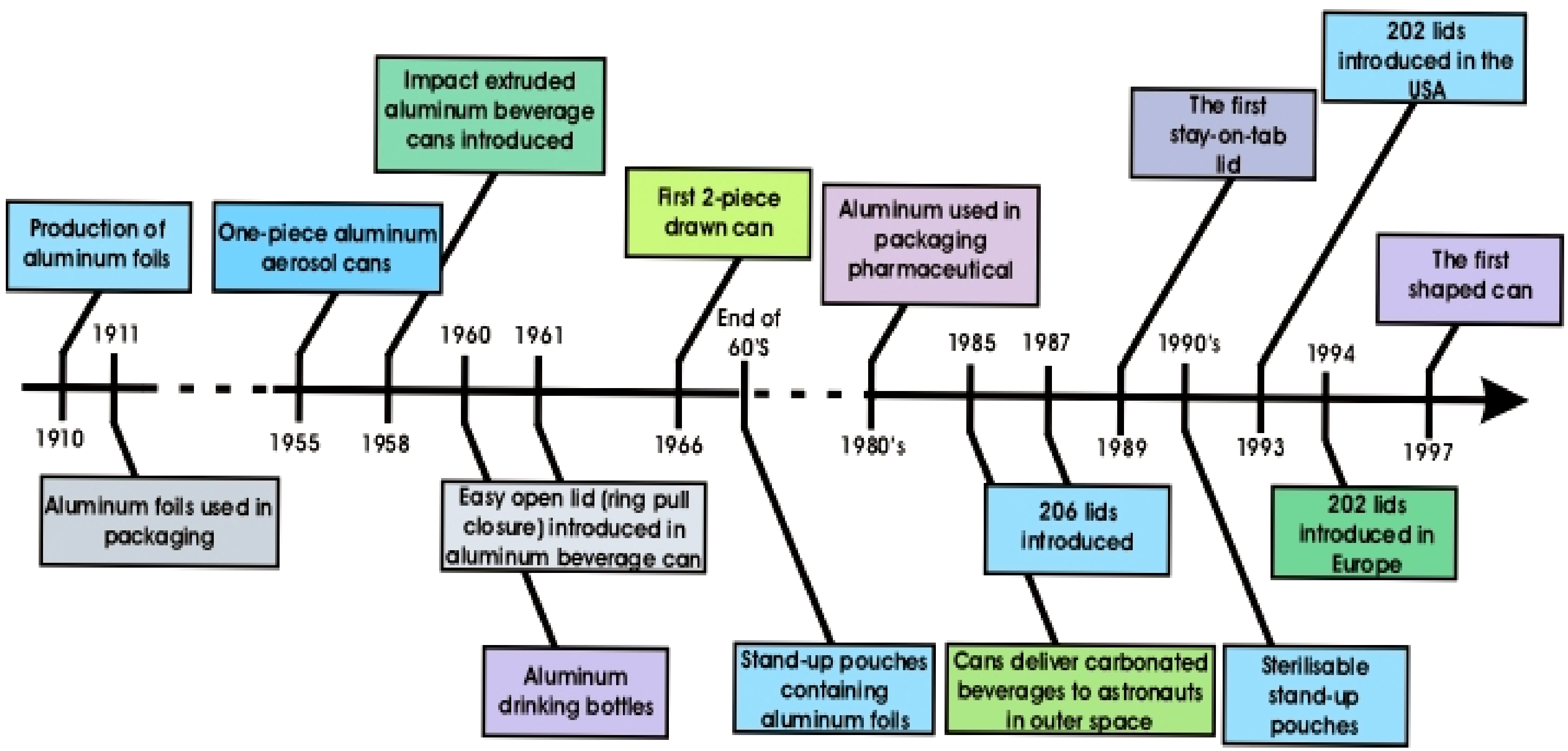

Figure 2.1: Aluminum in packaging.

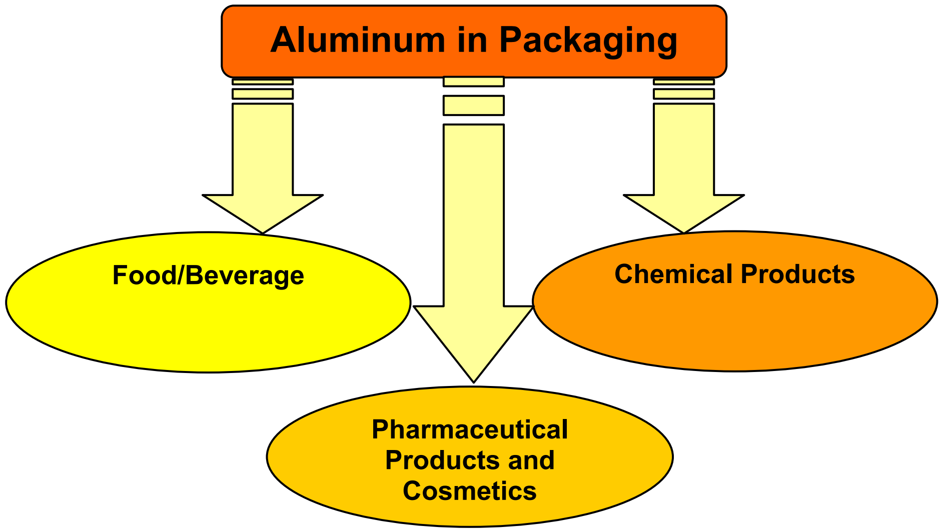

Figure 2.2: Uses of Aluminum in Packaging.

Material Properties of Aluminum

- lightweight
- good formability and good shape stability
- good thermal conductivity
- high reflectivity for light and UV rays
- excellent barrier properties
- corrosion resistance
- almost completely chemically neutral
- good printability
- complete recyclability
- physiological harmlessness

Figure 2.3: Material Properties of Aluminum which makes it a Superior Packaging Material [13].

2.2 Development of Aluminum Beverage Cans

Aluminum beverage cans are part and parcel of today's life for most Americans. We take these cans for granted most of the time, and do not think twice about it when using or discarding them. We do not realize that these cans have undergone nearly 70 years of amazing design and manufacturing innovation and evolution, starting with the birth of the steel can. Today's aluminum beverage cans are the result of years of hard work, and the fruit of new manufacturing technology. The can is not only lightweight; it is also structurally very advanced. The commercial can nowadays weigh only 0.48 ounce, compared to 0.66 ounce in the 1960s [14]. This is a reduction of almost 27%. Aluminum beverage cans have a thickness less than two pieces of paper, yet could withstand pressure of more than 90 pounds per square inch, about three times the pressure in an automobile tire [14].

All this started almost 70 years ago in 1935, when the first 3-piece steel beer can was produced by the Krueger Brewing Company (Figure 2.4a). This 3-piece can consisted of a rolled and seamed cylinder and two end pieces [14]. The design required that consumers use a pointed instrument to open it [15]. Some earlier designs also incorporated conical tops sealed by bottle caps (Figure 2.4b) [14]. The first canned soft drink was Cliquot Club ginger ale, which appeared in 1938. However, it was beset by leakage and flavor absorption problems from the can liner [16]. The problems were only solved in 1948, when the first major soft drinks packaged in a steel can were launched by Pepsi-Cola (Figure 2.5) and the Continental Can Company.

(a) (b)

Figure 2.4: The birth of the steel beer cans (a) and the bottle cans (b) (Source: Beer Can Collection of America [16]).

The first aluminum beverage can was marketed in 1958 by the Adolph Coors Company in Golden, Colorado, and introduced to the public by the Hawaiian brewery Primo [14]. This first two-piece aluminum beverage can was produced using the impact-extrusion process. The Coor's can was structurally weak, and had a capacity of only 7 ounces. However, consumer demands pushed the can to evolve further, with the introduction of the first easy-open lid in 1961. In 1963, Reynolds Metal Company introduced a new manufacturing process for producing 12-ounce aluminum cans, from which all modern can manufacturing processes are derived. It was used to package a diet cola called "Slenderella" [16]. Hamms Brewery in St. Paul, Minnesota begin to package beer in the 12 ounce aluminum can in 1964, and Pepsi-Cola and Coca-Cola soon followed in 1967 [14]. The first "206" (diameter of 2.5") lid was introduced in

1987, followed by the current “202” (diameter of 2.25”) lid in 1993. The current “stay-on-tab” lid has been around since 1989. To increase customer appeal and create a distinctive look for the product, the first shaped can from Crown Cork & Seal appeared in 1997 (Figure 2.6). A comprehensive time line of major developments in aluminum beverage can is shown in Figure 2.7.

Figure 2.5: Aluminum Beverage Cans used to Package Pepsi-Cola and Coca-Cola products in the 1960s [16].

Figure 2.6: Shaped Aluminum Cans from Crown Cork & Seal [17].

Today, the aluminum beverage can is the primary packaging container used in the soft drink and beer industries in the United States and the world. Steel cans have been virtually displaced by aluminum cans [14], except in some parts of Europe and Asia. Aluminum beverage cans have undergone many changes throughout the years, but cannot stay stagnant if they want to be ahead of the competition, especially against PET plastics in the soft drink segment, and glass in the microbreweries segment [18]. Customer demands and sustainability concerns will be the main factors dictating changes in the future.

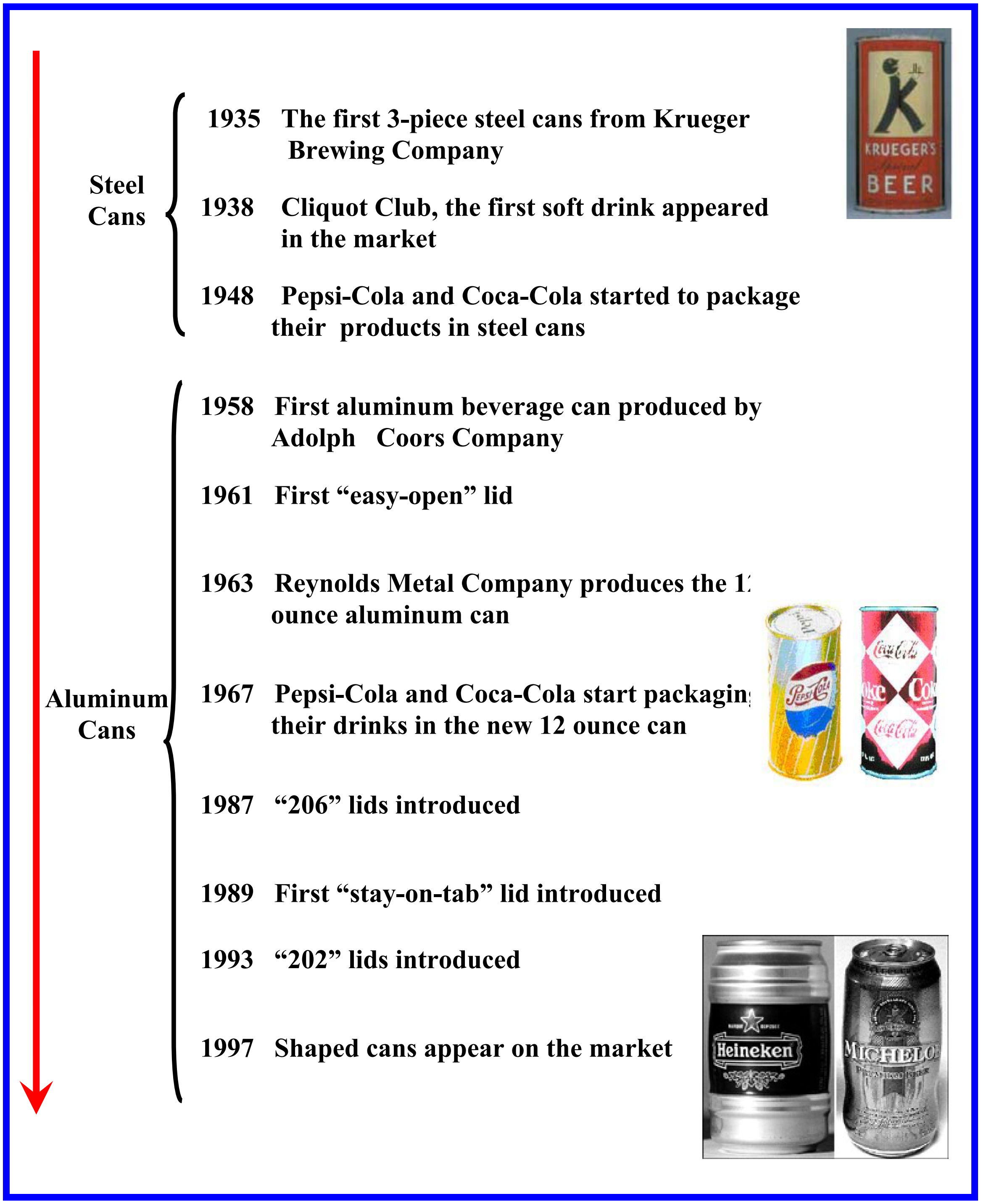

Figure 2.7: Major Developments in Aluminum Beverage Cans

2.3 Modern Aluminum Beverage Can Design

Modern aluminum beverage cans are designed using the latest tools, such as finite element analysis [19] and the most advanced manufacturing processes [14], [20]. Aluminum cans today are not only lightweight and strong, but also provide customer appeal, and are effective at keeping food and beverages fresh. Figure 2.8 shows the anatomy of the modern aluminum beverage can.

Modern aluminum beverage cans consist of 2 major pieces, the body and the lid (including the stay-on tab), as opposed to the earlier 3 piece design (bottom, body and lid) for steel cans. The body is manufactured using an impact extrusion process known as two-piece drawing and wall ironing, first introduced by the Reynolds Metal Company in 1963. The body is made out of an aluminum alloy AL3004, with composition by weight of 1% manganese, 0.4% iron, 0.2% silicon and 0.15% copper. Its thickness is about 0.003 inches, thicker at the bottom for added strength [14]. The structural strength of the aluminum can is enhanced by the shape of the bottom, which curves inward to assume a dome shape. The top of the body is usually necked to accommodate the lid, which has grown smaller in diameter over the years.

The lid or can end is an integral part of the can, made out of aluminum alloy AL5182. It contains less manganese and more magnesium, thus making it stronger than the body [14]. The center of the lid is usually drawn up to make a rivet for the tab. The tab is used to open the can, and is usually scored to make it easier to open. Over the years, the diameter of the lid has progressively become smaller and smaller; the “202” lid is the standard today.

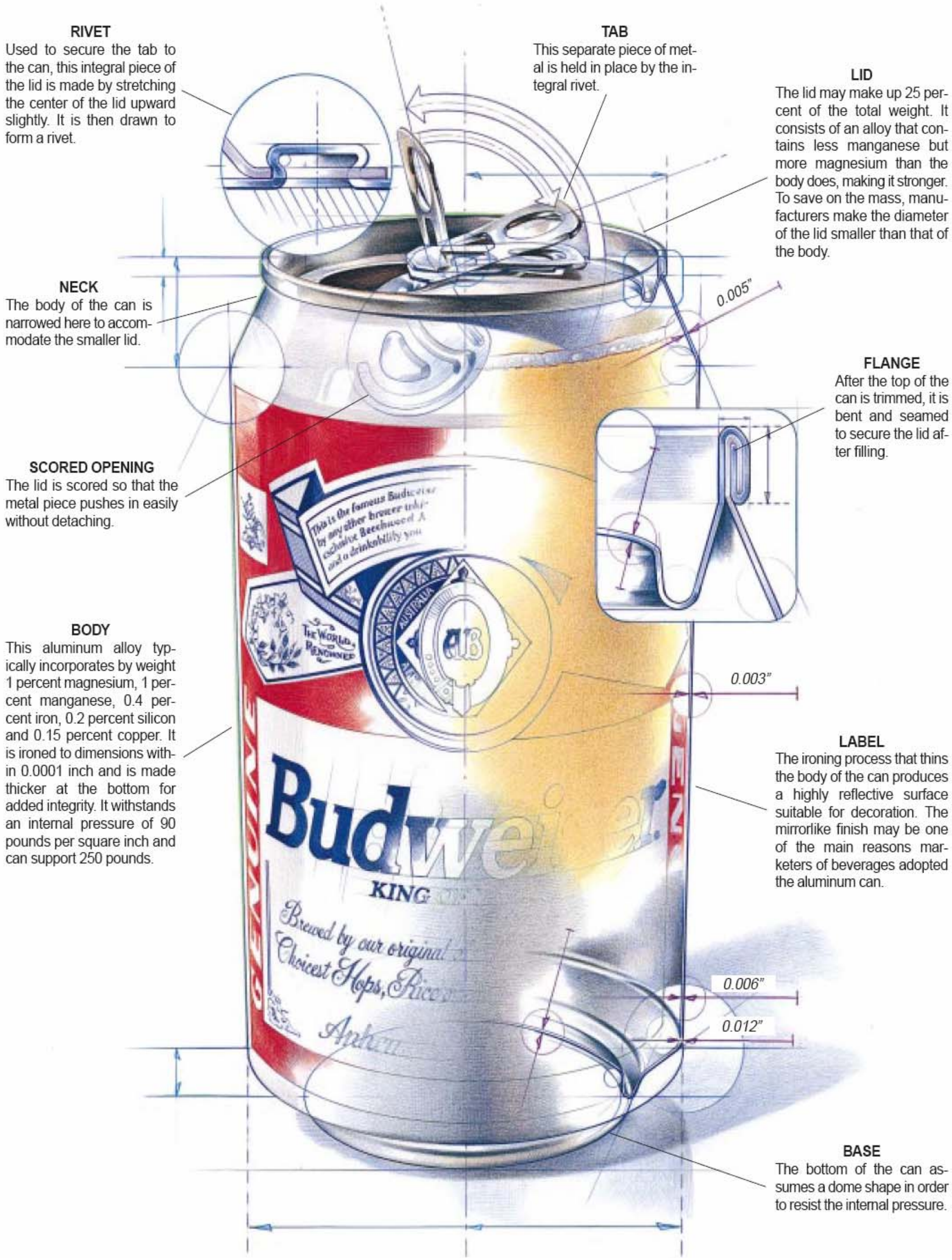

Figure 2.8: Anatomy of the Modern Aluminum Beverage Can [14].

The aluminum beverage can the lid made out of a stronger alloy than the body because the top needs to be able to withstand top loadings during stacking. It must also be strong enough to be double-seamed. Current aluminum beverage cans come in different sizes, from 4 oz up to 32 oz of liquids. In addition, the lid also comes in various sizes and colors, with the "202" type the most popular today. Table 1 shows the various can sizes and lids manufactured today.

Table 2.1 Various Can and Lid Types

Aluminum Beverage Can Sizes (oz)				**Aluminum Beverage Can End Types and Sizes**
32	25	16	12	202 (2.25" diameter)
11.3	10	8.4	8	204 (2.38" diameter)
6.8	5.5	4		206 (2.5" diameter)

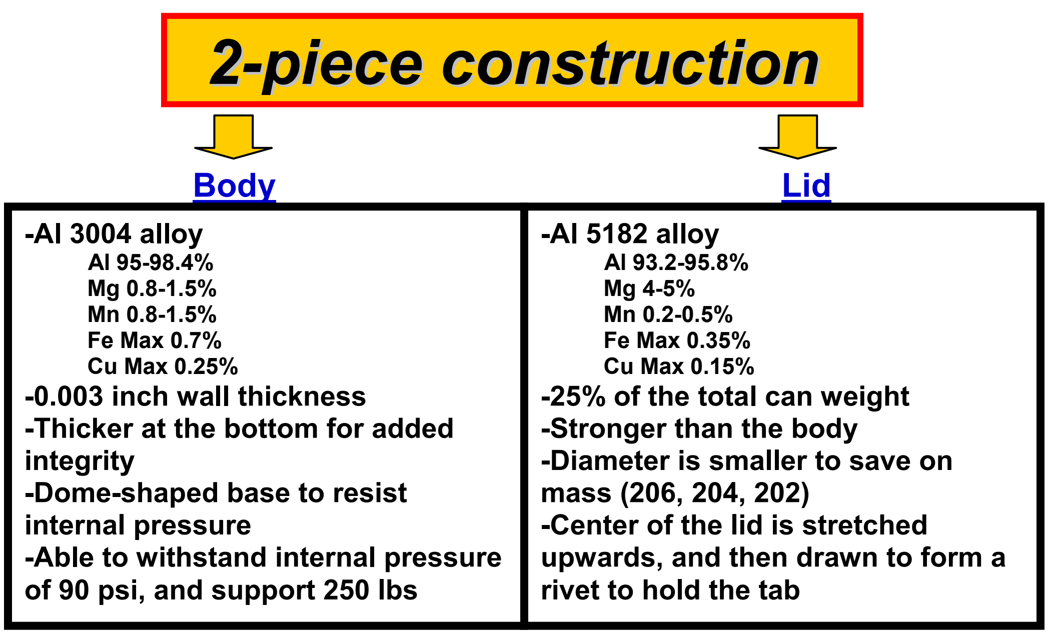

Figure 2.9: Construction of Modern Aluminum Beverage Cans

2.4 Aluminum Beverage Can Manufacture

Aluminum beverage can manufacture starts with uncoiling rolls of aluminum sheet. Each coil can weigh up to 25,000 lbs. AL3004 alloy is used to manufacture the body and AL5182 alloy for the lid or can end. To manufacture the body of the can, after uncoiling, the sheets are passed through a lubricator. Here, a thin film of lubricant is applied to the surface of the sheets, which pass on to the cupper, where circular blanks are cut from the sheet and formed into cups. This process, called backward extrusion, can produce 2500 to 3750 cups per minute. A series of tooling dies is then used to redraw and iron the cups until the specific shape and specifications of the can body are obtained. After that, the open end of the can is trimmed to a uniform height. The redrawing and ironing processes is shown in Figure 2.10.

The can is next washed and dried to prepare for application of internal coatings and outside labels. A base coat of lacquer is next applied to the outside surface of the can, before it goes into an oven to be cured. Graphics are then printed onto the outside surface, using up to 6 different combinations of color before a thin film of lacquer is applied. Lacquers are also applied to the bottom of the can. Next, the whole thing goes into another oven to be cured. Another film of lacquer is applied to the internal surface of the can, which goes into another oven to be cured.

The can next goes though a machine called the waxer, where another film of lubricant is applied to the edges of the can in preparation for necking. A

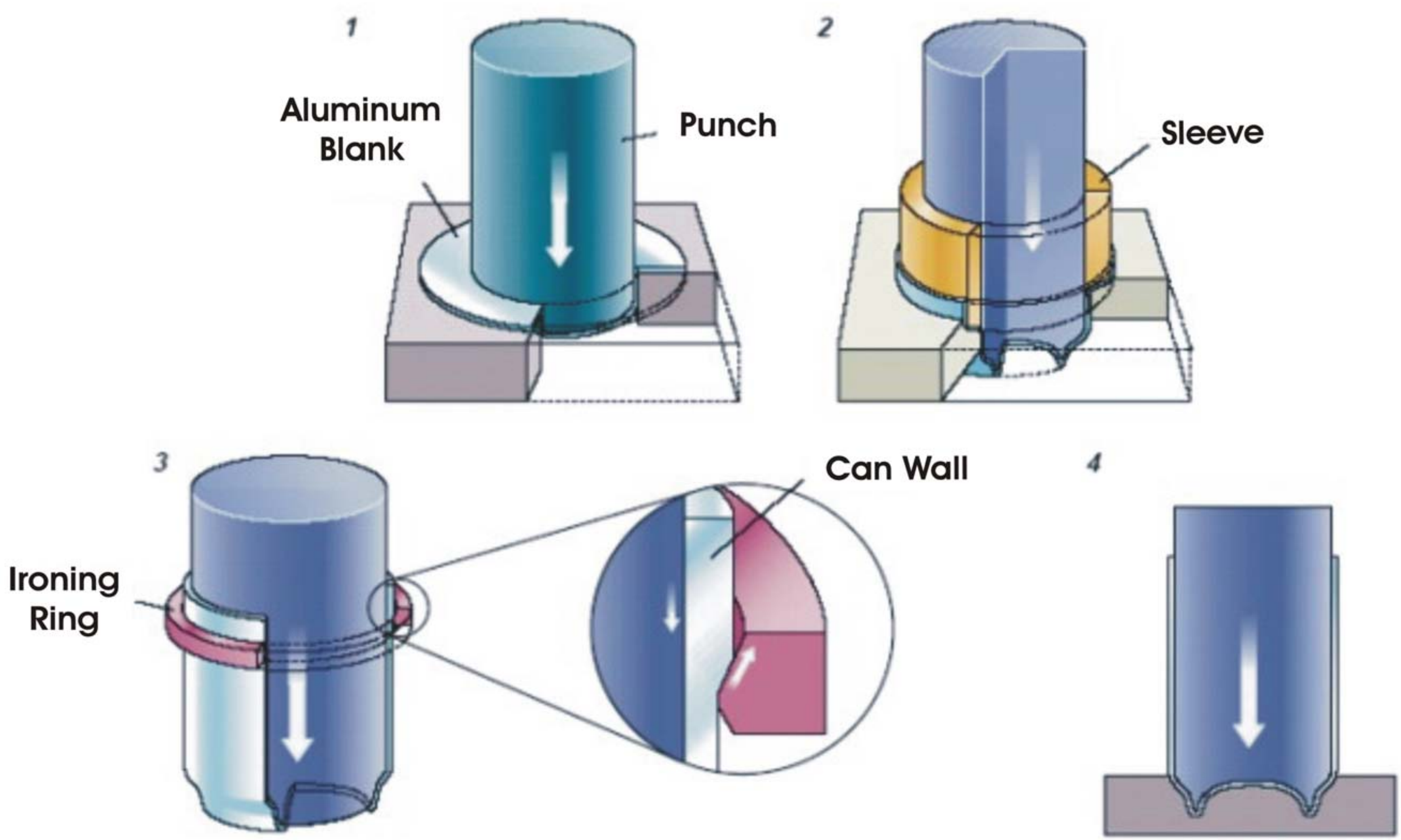

Figure 2.10: Aluminum Beverage Can Drawing and Wall Ironing Processes

machine called the die necker then gradually rolls the top opening down to specific diameters, depending on which size of lid will be used. The flanger then rolls back the top of the can, in order to form a lip to which to attach the can end after filling. The outer dome is next reprofiled for stackability, or inner dome reformed for strength. Quality inspection is performed next to check for pinholes or other damage. Cameras are used to check for inside contamination before the cans are palletized to be shipped to customers. Customers such as soft drink companies then fill the cans with their product, and finally the lid or can end is attached and seamed. Figure 2.11 shows the physical transformation of the can through each process.

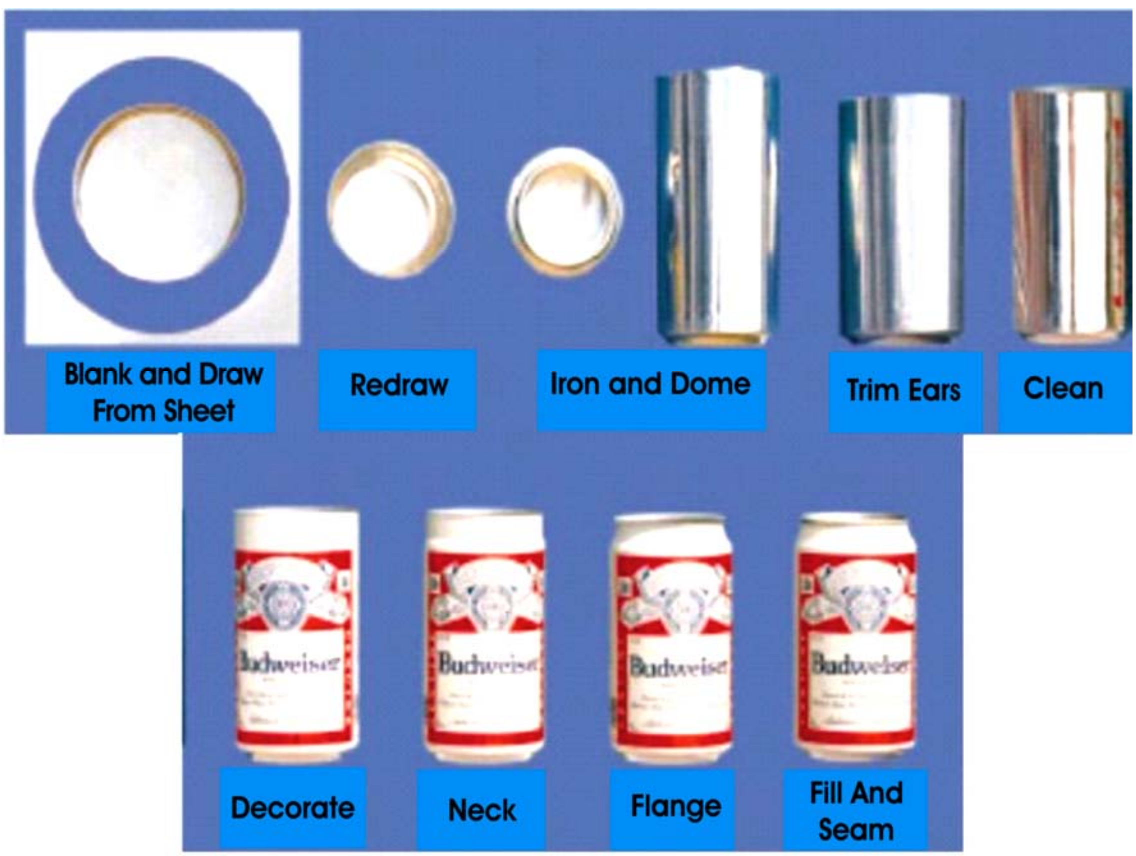

Figure 2.11: Transformation of Aluminum Beverage Cans During Manufacture [14]

The lid or can end also starts off with coiled aluminum sheets. In this case, the sheet is AL5182. After being lubricated, the sheets go into a shell press. A circular disc is blanked and then formed into a shell. This process can produce up to 5,500 shells per minute in a modern plant. The shell is then discharged through a curler, which forms the precise shape required for the double seaming operation to attach the lid to the body. A liquid sealing compound is then applied to the end, and the shells moved to a conversion press where the score is formed and tab attached. After quality control checks, the lids are shipped to the customers.

2.5 Aluminum Beverage Can Recycling

Aluminum beverage can recycling was started as a result of the “Ban the Can” campaign in the seventies. Used aluminum beverage cans were considered an eyesore, and manufacturers had to set up recycling centers to deal with this issue. In addition, the 1973 OPEC oil crisis forced manufacturers to find a more energy-efficient way to manufacture aluminum beverage cans. They found that recycling only consumes 5% of the energy needed to produce the same can from virgin metals. At a 25% recycling rate, the aluminum can is more energy efficient than the bi-metal can, and with 60% recycling it becomes competitive with the returnable bottle [21].

The aluminum beverage can recycling process in a modern recycling plant is illustrated in Figure 2.12. Used beverage cans (UBCs) come in bales weighing

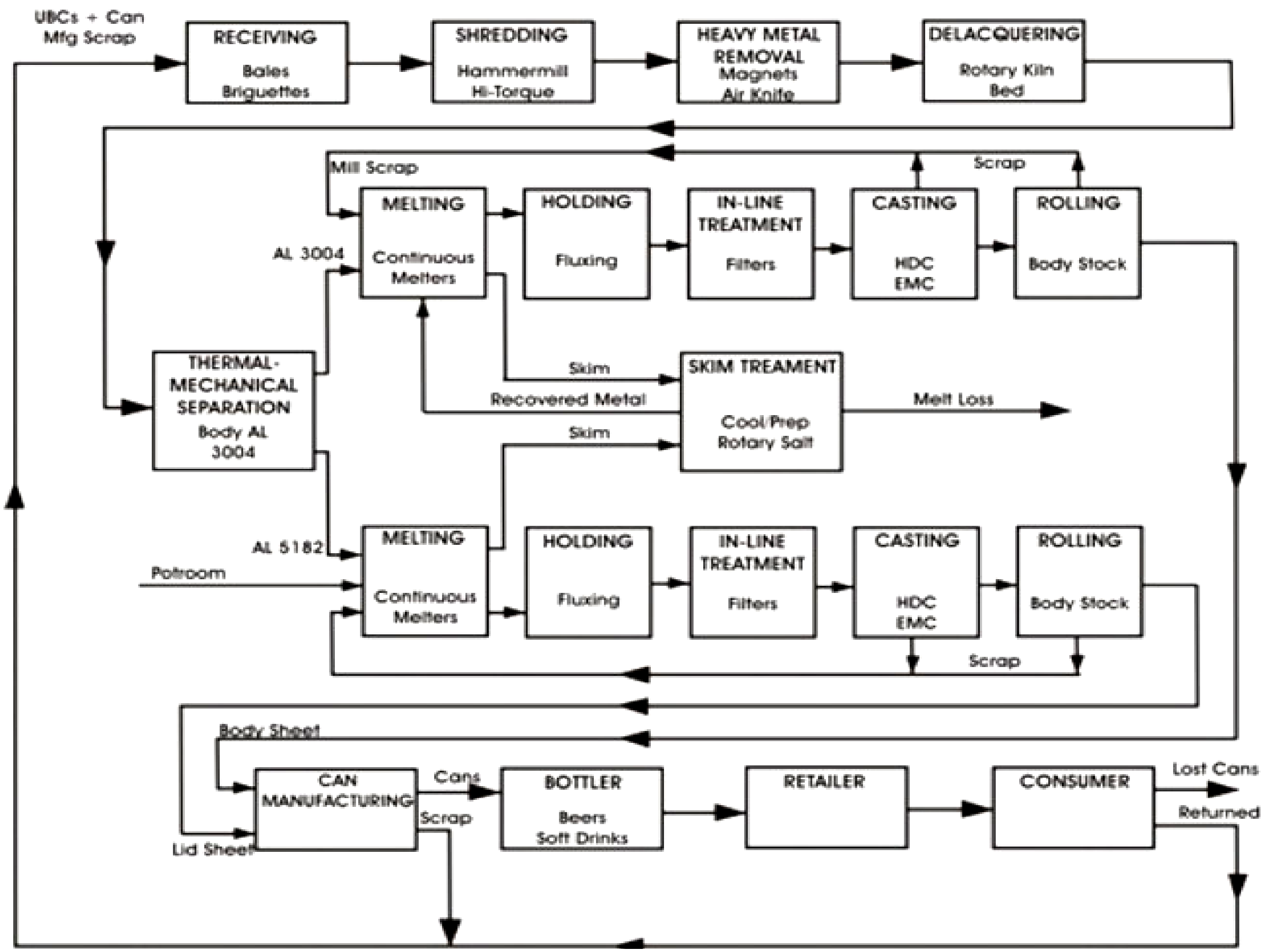

Figure 2.12: Aluminum Beverage Can Recycling Process [22], [23]

approximately 400 kg, or as briquettes with maximum density of $500 kg/m^3$ [22]. The first step in recycling UBCs is to shred them to ensure that no trapped liquid or extraneous material reaches the melters, which might cause serious damage or injuries [22] & [23]. After being shredded, the UBCs pass through a magnetic separator to remove any ferrous contaminants. Nonmagnetic and nonferrous materials such as lead, zinc and stainless steel are separated using an air knife.

The next step is delacquering, usually carried out in two ways. The first method is to expose the UBCs to a "safe" temperature over a long period of time; the second method is to heat the UBCs to a temperature just below the melting temperature of the alloys for a short time. The UBCs then move to the next stage, the thermal-mechanical separation process. In this stage the temperature is held constant at a specific level in a neutral atmosphere; by gentle mechanical action the AL 5182 alloys are broken into small fragments, along the grain boundaries weakened by the onset of incipient melting [22], [23]. The fragmented AL 5182 particles then pass through an integrated screen and are transported to lid stock melters, and the AL 3004 particles are sent to body stock melters.

Chapter 3

Sustainability Issues of Aluminum Beverage Cans

One of the most well known definitions of sustainability is from the 1987 Brundtland Commission Report. It defined sustainability simply as "meeting the needs of the present without compromising the ability of future generations to meet their own needs" [2]. Economic viability, social responsibility and environment protection are the three pillars of sustainable development [24]. Figure 3.1 illustrates all major components of sustainable development, encompassing the three pillars of sustainability.

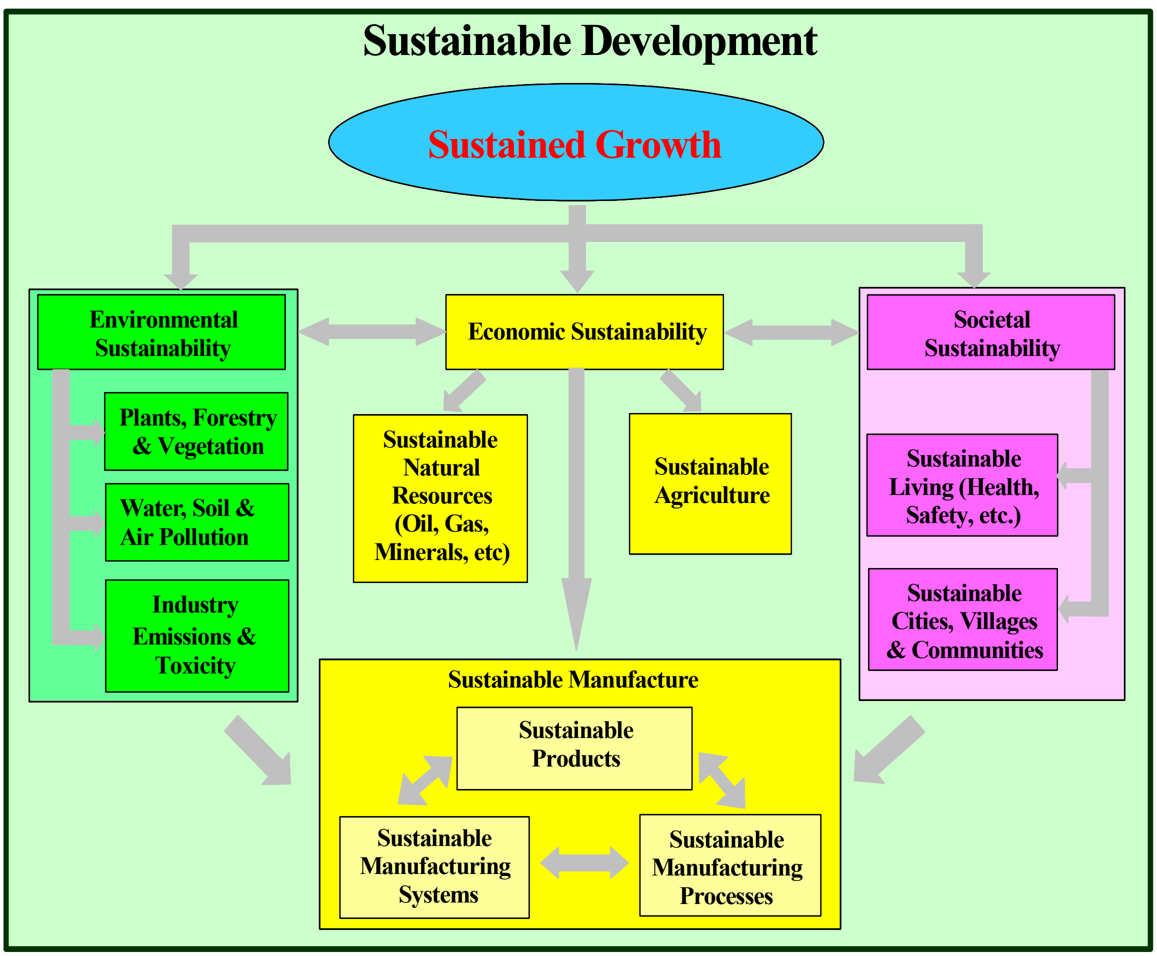

Figure 3.1: Sustainable Development [25]

The application of sustainability ranges from sustainable city and urban development to sustainable consumer products. Current concepts regarding sustainability are more concerned with determining the economic and social dimensions of sustainability and linking these with the ecological dimension [24]. This approach is referred to as "corporate social responsibility" [24]. Comprehensive, global sustainability heavily depends on collective and unified effort of the global community involving multi-disciplinary approach [1].

3.1 Sustainability Development in the Aluminum Industry

Aluminum is probably one of the most important and essential metals in the industrialized world today. Its strength, conductivity, recyclability, and light weight make it ideally suited to the needs of a highly mobile and technologically sophisticated world [26]. Aluminum also fits well in the concept of sustainability because it is the most environmentally sustainable material available to our increasingly resource-conscious planet [26]. Aluminum applications began in 1886 when Hall and Héroult discovered how to mass produce aluminum through electrolysis. In 1900, the annual output of aluminum was only 1000 tonnes, but this figure rose to 20 million tonnes by the end of the 20th century. In 2000, the United States shipped $6.1 billion worth of aluminum [26]. This makes aluminum the world's second most used metal [27]. Figure 3.2 shows the world's uses of aluminum, with the transportation sectors consuming the most aluminum compared to other sectors. The packaging sector consumes 20% of worldwide aluminum usage, tied with the construction sectors.

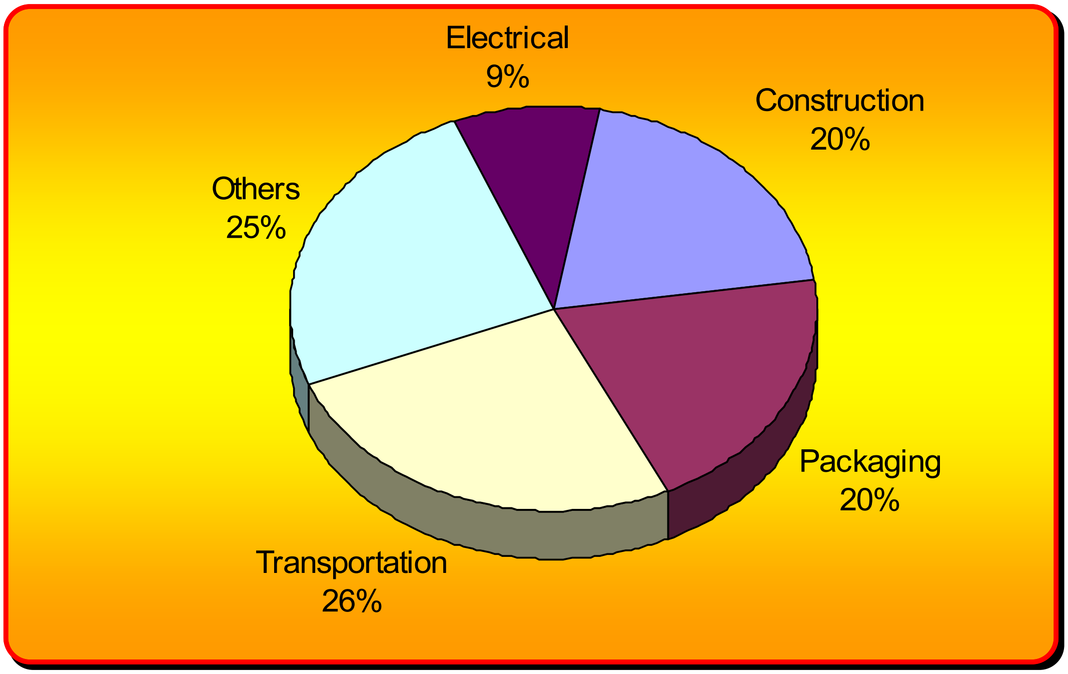

Figure 3.2: World Aluminum Consumption in 2000 (Data from [27])

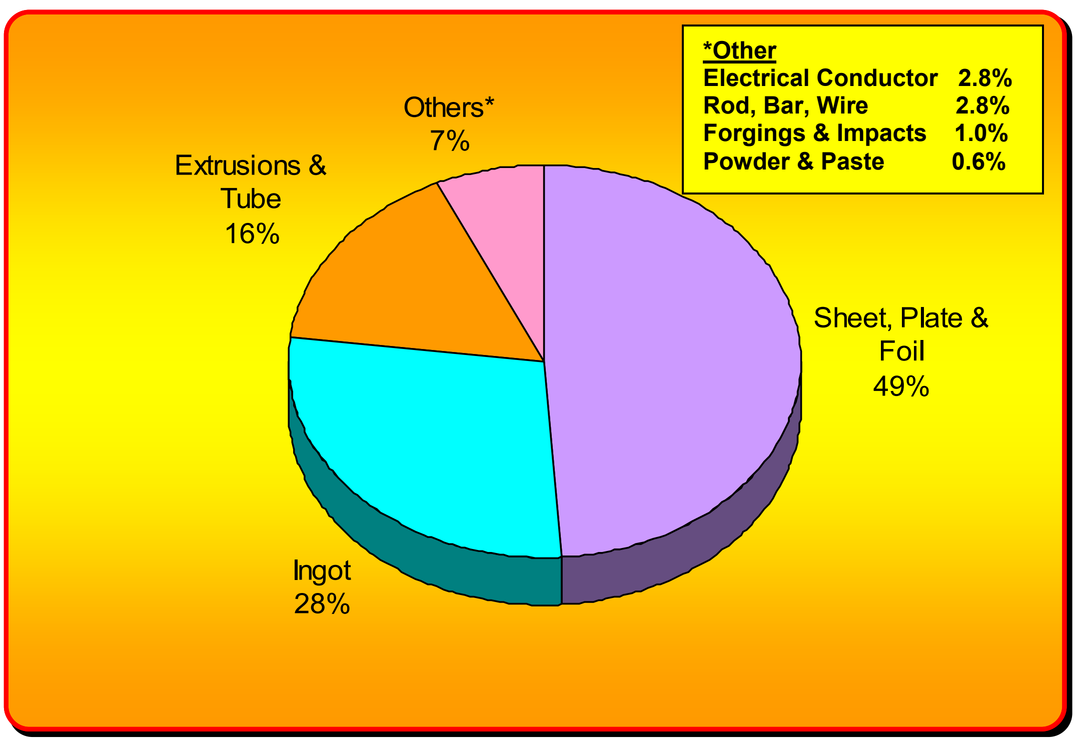

Figure 3.3: US Aluminum Shipments by Product Form in 2000 (Data from [26])

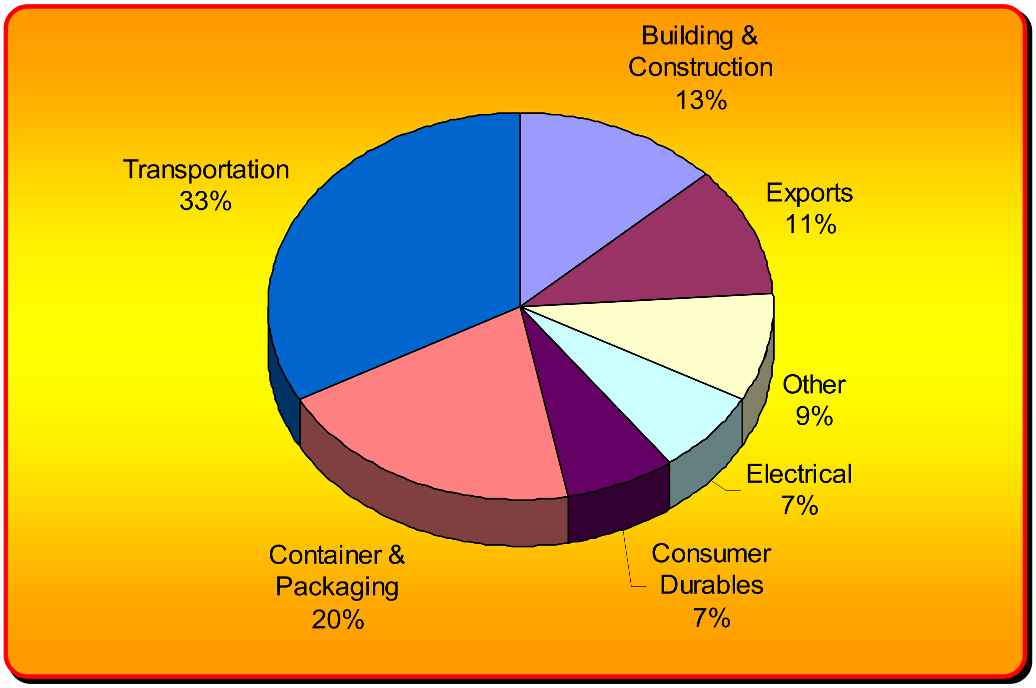

Figure 3.4: US Aluminum Shipments by Major Markets in 2000 (Data from [26])

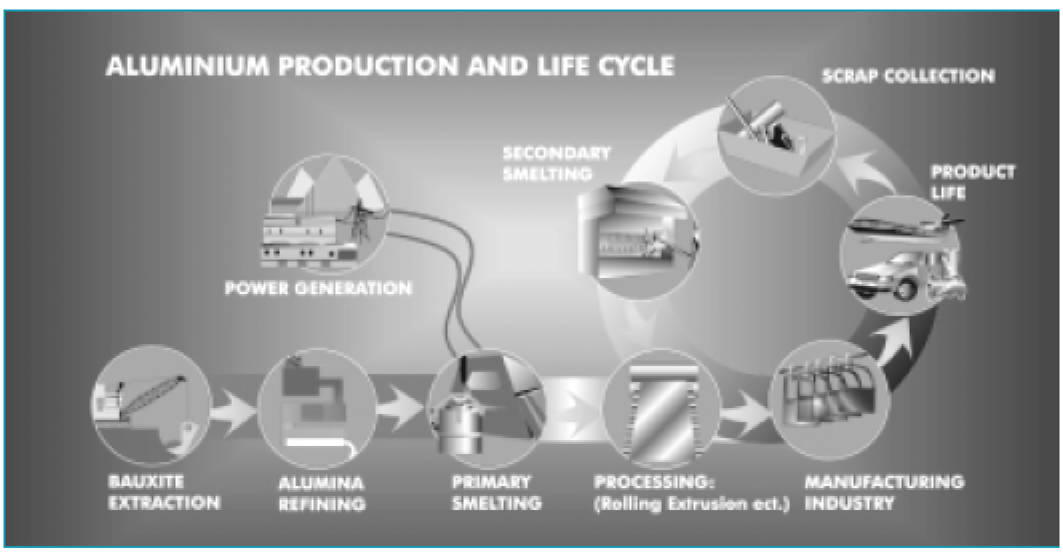

Figure 3.5: Aluminum Production and Life-cycle [27]

Figure 3.3 shows US aluminum shipments by product form and by market in Figure 3.4. Aluminum in the form of sheet, plate and foil constitutes the largest shipment in the US in 2000, while the transportation sector consumes 33% of US aluminum shipments, closely followed by the packaging industry at 20%. Most of the uses of aluminum sheets, plate and foil are in the packaging industry, for making aluminum beverage cans, food containers etc. Figure 3.5 shows the life-cycle of a typical aluminum product, starting with bauxite mining and extraction, ending with recycling by collecting scraps and secondary smelting.

Two important sectors for aluminum consumptions are the transportation sector, specifically the automobile industry, and the food packaging industry. Due to the superior weight to strength ratio, aluminum is widely used to make light and fuel-efficient cars. During an automobile's production, one kilogram of aluminum can replace two kilograms of conventional heavier materials, thus helping in reducing the automobile's weight and cutting down fuel consumption and emissions while retaining or improving the vehicle's safety [27]. This translates into a reduction of 20 kilograms of CO_2 [27] for every kilogram of aluminum used to replace conventional materials used in automobile manufacture. It has been forecasted that by 2020, there will be a 35% increase in CO_2 emissions from all vehicles, while an increased use of aluminum in vehicles would reduce these statistics to 28% [27]. Therefore, the use of aluminum is one important option in sustaining the automotive industry.

Aluminum used in the food packaging industry helps to preserve food quality, reduces wastes and provides convenience for consumers [13], [27]. Its excellent properties described in Chapter 2 and shown in Figure 2.3 help it to saves about 30% of the world's food from wastage [27]. Only about 10% of the energy consumed in the production of foodstuff is attributed to packaging, with 50% of energy consumed during primary production of the foodstuff itself and 35% for the food preparation and handling [27]. The public used to have the misconception that packaging, be it aluminum beverage cans or aluminum foil, creates environmental pollution. However, the fact is that packaging saves ten times more waste than it creates [27].

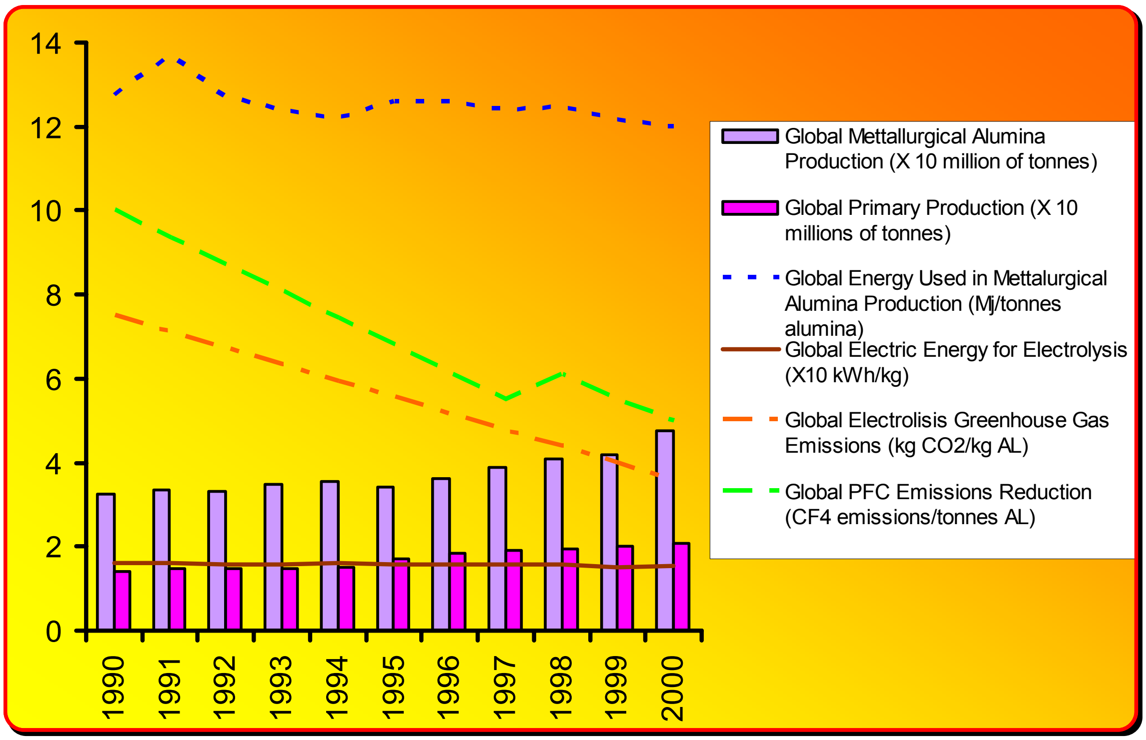

Figure 3.6: Global Aluminum Production Data (Compiled using data from [27])

Over the years, the whole aluminum industry has improved in terms of economy, environment and society point of view. Figure 3.6 shows the world trend in aluminum production. Although global alumina production and primary production of aluminum has been steadily increasing over a period of ten years from 1990 to 2000, energy consumption and outputs from productions such as green house gases and PFC have been on the decline. This shows that it is possible to have a sustainable growth and development without sacrificing economic profits or ecological side effects. Both, the economy and the environmental sustainability can go hand in hand. Improvements in green house gas emissions and energy consumption reductions in production mainly have to do with technological advancements over the years in production and manufacturing processes. Aluminum is derived from bauxite ores, which has to be mined. About 120 million tonnes are extracted annually, and the global commercially available bauxite reserves will last for more than 200 years [28]. Although only a small percentage of bauxite, about 6%, is mined in the rain forest region (2.4 square kilometers is used annually, about 0.00002% of the world's rain forest), extensive rehabilitation of the land is still carried out by the aluminum industry after extraction of the ore [28]. In 1990, a bauxite mine in Western Australia was awarded the "Global 500 Roll of Honor for Environmental Achievement" prize by the United Nations for their role in rehabilitation and environment protection.

Most companies involved in the aluminum industry have adopted the concept of "corporate citizenship", where consideration has been given to a company's social responsibility and to concepts of socially correct business dealings, while at the same time bearing the aspects of sustainability in mind [29]. The first step in protecting society in the sustainable aluminum industry starts at the refinery plant level. Figure 3.7 shows statistics for global accident rates at smelters, refineries, mines and all aluminum plants. A downward trend is

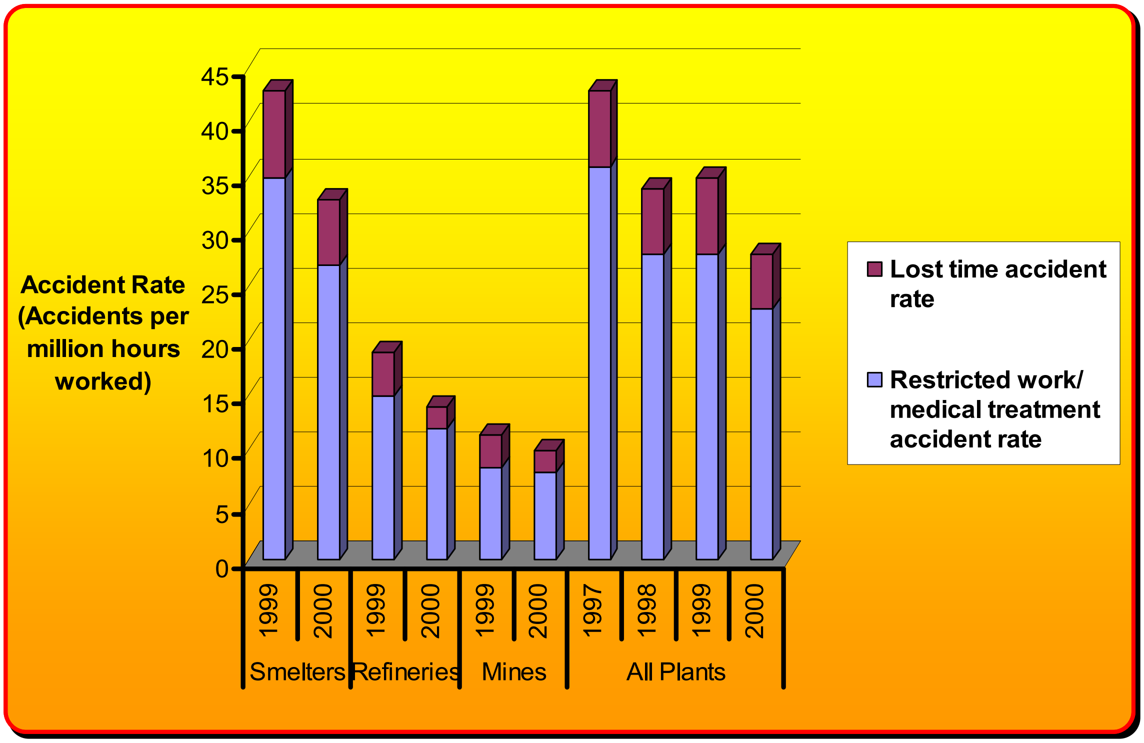

Figure 3.7: Global Accident Rates in Aluminum Production (Data from [27], [29])

observed in all categories, and therefore showing that sustainability at the societal level, in terms workers' safety and welfare, in the aluminum industry is on the rise. If we look at the product level, aluminum products have really revolutionized the human society. From transportation to food packaging, aluminum is indispensable at the societal level. We have seen how aluminum is used in automobiles not only to increase fuel efficiency and reduce CO_2 emissions, but also enhance to an automobile's safety. Crash tests of automobiles show that aluminum absorbs at least as much energy as steel structures [29]. In addition, aluminum is also used in airplanes to reduce weight. Today's Boeing 747 aircraft is comprised of 80% aluminum. This helps the airline industry to transport about a third of the world's trade goods in value, and it carried 1.5 billion passengers in 1999. Both use of aluminum in automobiles and airplanes have greatly increased human and goods mobility. Use of aluminum in the packaging industry has helped protect society against food contamination as well as preserving food and beverages for a longer period of time. Its properties shown in Figure 2.3 make aluminum one of the most effective and long life packaging materials. Even an extremely thin layer of foil help maintains the freshness of foods that quickly deteriorate, such as milk and enables medicine to be transported and stored in tropical regions with high humidity [29].

From the systems perspective, the aluminum industry provides jobs to countless people and is vital economy drivers for many countries. Kentucky has a huge aluminum industry and if it were a country, it would have the most concentration of aluminum plants in the world, with an average annual worker's wage of $46000. The United States is one of the largest producers of primary aluminum metal in the world with shipments worth $6.1 billion in 2000 [26]. Aluminum contributes 50% of Jamaica's exports and provides employment to over 4000 people there, with the least qualified workers earning up to four times the legally required minimum wage in that country [29]. In Brazil, aluminum companies provided elementary education for the children of their employees and donated education materials to over 25000 school children [27]. The German aluminum industry employs about 75000 people with a total wage and salary bill of four billion euros [30], making it one of the largest industries in that country. In Ghana, the Volta Aluminum Company contributes $200 million annually to the economy, making it the fifth largest contributor of foreign exchange to the country [27].

Another critical aspect that contributes to the sustainable development of the aluminum industry is recycling. Aluminum is an “energy bank” that can be recycled over and over again without quality loss. Its amazing recyclability ensures that a deposit made into this bank will preserve its value [26]. The suitable phrase for consumption of aluminum is that it is used and not consumed [31]. A large number of secondary aluminum metals from the “aluminum pool” can be recycled and reused. A widely known fact is that aluminum products can be recycled and remanufactured endlessly with only 5% of the energy and emissions originally required to produce the virgin product [26]. It takes about 95000 Btus of energy to make one pound of primary aluminum from bauxite ore, but only 4300 Btus from scrap, or secondary aluminum metal [32]. Figure 3.8 shows the worldwide recycling rate of various aluminum products with respect to markets in 1990 and 2000. Generally, the trend is pretty encouraging with increased recycling rates in all markets, with the exception of one; the aluminum beverage can market, which decreased from 61% in 1990 to 59% in 2000. As stated earlier, aluminum recycling is a critical factor in ensuring the sustainable development of the aluminum industry, due to the fact that recycling contributes to the three pillars of sustainability. Recycling is beneficial to the environment, reducing wastes and scrap. It also reduces the need for clearing land for fresh supply of bauxites. Recycling is economically viable, since aluminum is an

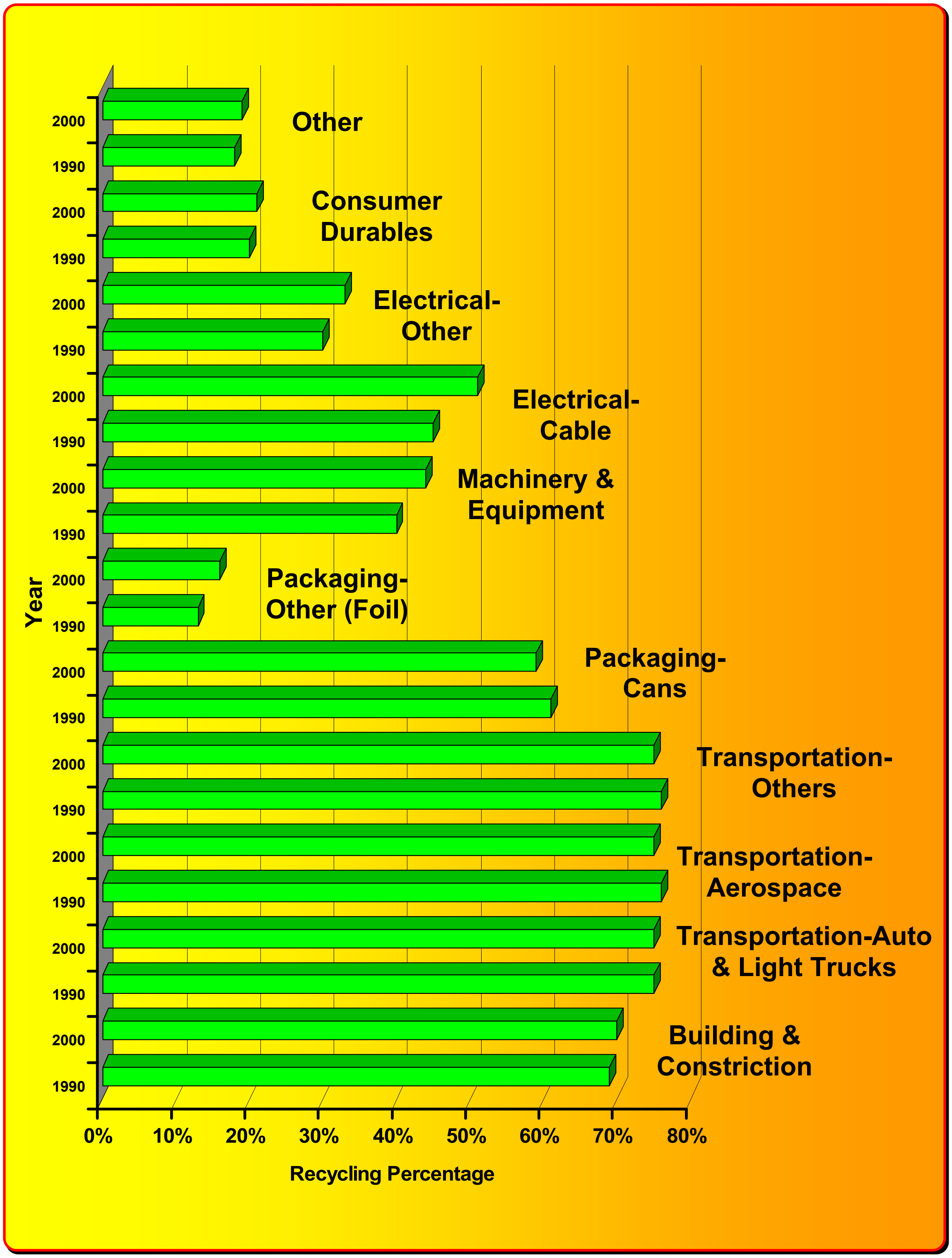

Figure 3.8: Worldwide Collection (Recycle) Rates by Market (Data from [33])

“energy bank”, and producing aluminum from scrap only consumes 5% of the energy used to extract aluminum from bauxites. The recycling industry creates jobs for society, and helps them to live in a cleaner and better environment.

The aluminum industry as a whole is moving in the right direction in achieving a sustained growth and development. However, one particular area of concern in the aluminum industry is the aluminum beverage can market. One obvious factor that may threaten the sustainability of the aluminum beverage can is its declining recycling rates. We will further analyze the sustainability of the aluminum beverage cans in the next section.

3.2 The Sustainability of Aluminum Beverage Cans

If we look at the historical development of the aluminum beverage can, including its “ancestor”; the 3-piece steel can, the aluminum beverage can has been around for almost 70 years. It is a well-developed and mature product in terms of product design and development. As with other mature products in the market, the innovation curve is not as steep as with a newly introduced product. Without product innovation and improvement, the sustainability of the aluminum beverage can may be in jeopardy. Figure 3.9 shows the relationship between innovation and sustainability. From the product point of view, innovation equals increased sustainability. The major factors affecting a product’s sustainability are shown in Figure 3.10. Six factors have been identified, and they are a product’s functionality, environmental impact, societal impact, recyclability/ remanufacturability, manufacturability, and resource utilization and economy [35].

In order to enhance the sustainability of the aluminum beverage can, we need to analyze the market to see which of the six factors are most important for the can.

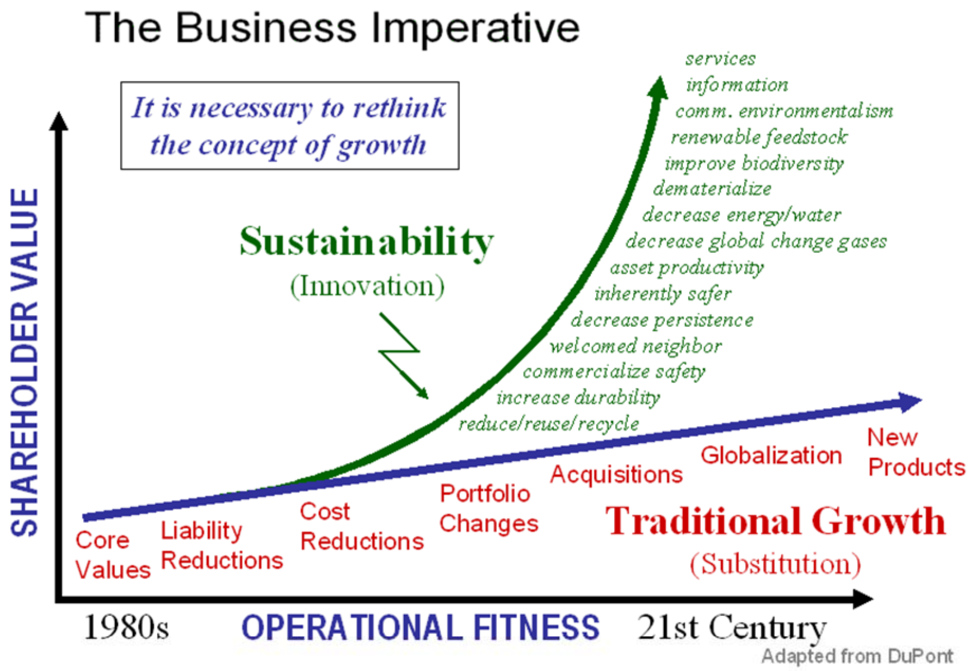

Figure 3.9: Innovation and Sustainability Relationship [34]

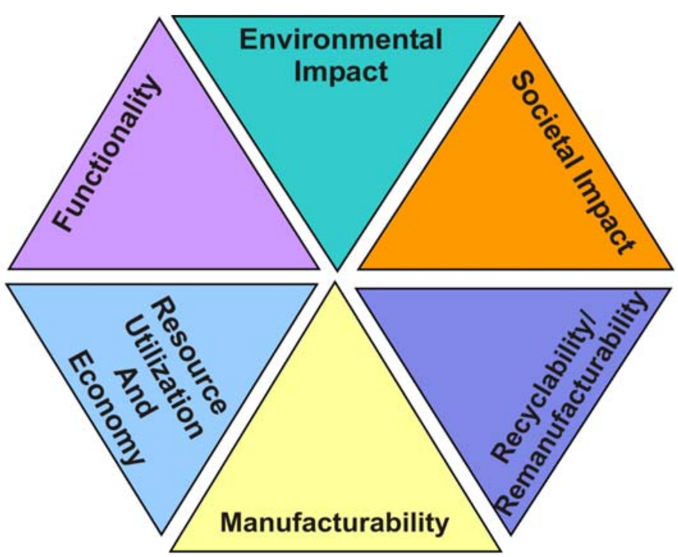

Figure 3.10: Factors Affecting Product Sustainability [35]

The United States is the world's largest consumer of aluminum beverage cans. It produces 300 million aluminum beverage can a day, and 100 billion cans a year [14]. The industry's output in the US is equivalent to one can per American per day, and outstrips the production of nails and paper clips [14]. According to the US Bureau of Census, the US aluminum industry employed about 141,000 people with total industry shipments estimated at $38.8 billion. According to the Aluminum Association Inc., aluminum beverage cans account for 100% of the total US beverage can market in 2002 [36]. This however is not the case in Europe, where the aluminum beverage can is facing serious competitions from steel and plastic containers.

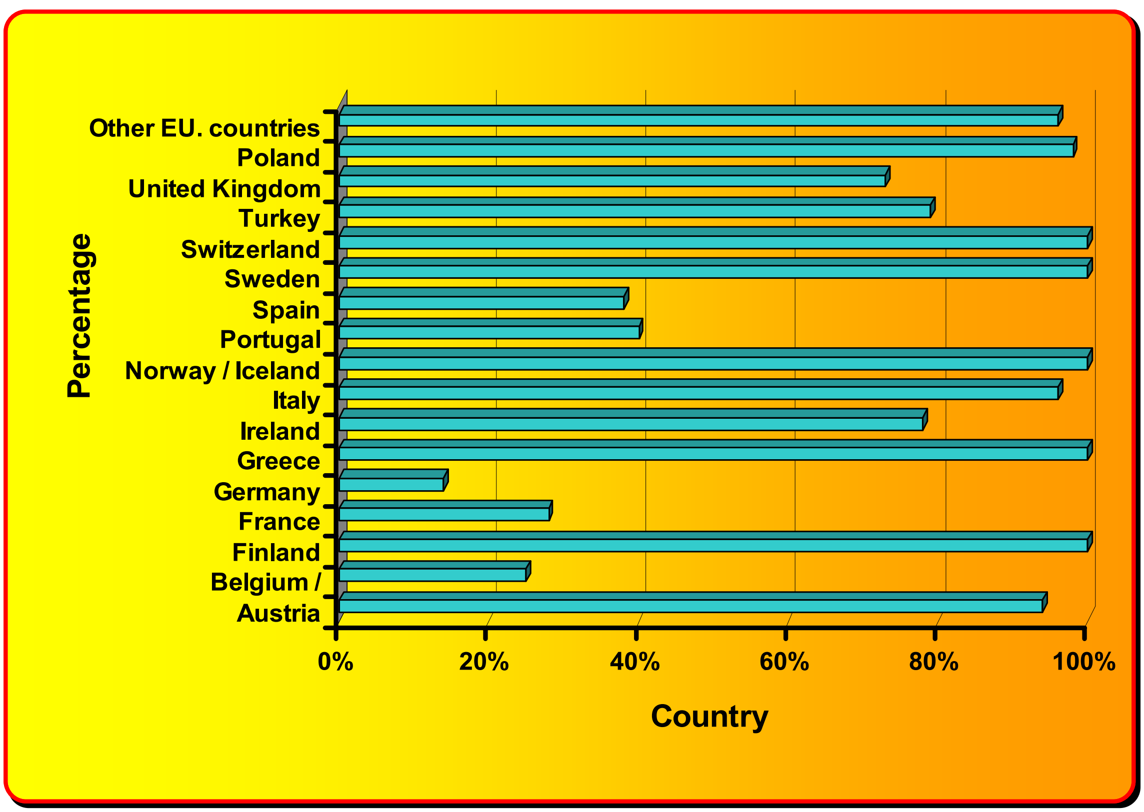

Figure 3.11: The Aluminum Beverage Can's Market Share in 2002 in Europe

(Data from [37])

Figure 3.11 shows the aluminum beverage can's market share in Europe in 2002. In several developed countries in Europe such as France, Germany, Portugal, and Spain, the market share of aluminum beverage can is less than 50%. As a result of competition, the annual growth rate for the overall aluminum container market slowed dramatically between 1990 and 2000 [26].

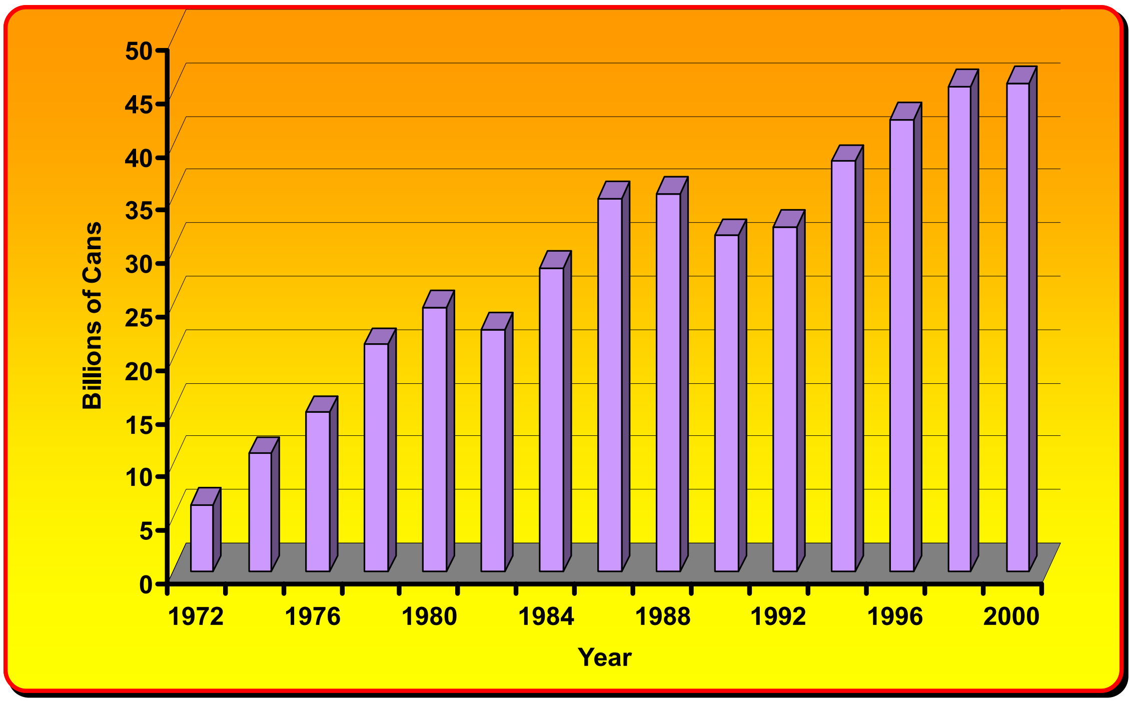

Figure 3.12: Aluminum Beverage Cans Discarded in the United States

(Prepared using data from U.S Department of Commerce & Bureau of Census)

Domestically, although the aluminum beverage can is dominant in the beverage can market, the aluminum beverage can recycling rate has been on the decline for the past few years. Figure 3.12 shows an increasing trend of the number of aluminum beverage cans discarded in the US from 1972 to 2000. An increasing trend is also observed in Figure 3.13 for the number of aluminum beverage cans being recovered for recycling from 1972 to 2002. However, the collection rate has not been able to keep up with the number of cans being discarded, and as a result, the recycling rate of aluminum beverage can has been on the decline since 1992. This trend is shown if Figure 3.14. The declining rate of aluminum beverage can recycling in the US is worrisome because recycling is one of the strong points of the aluminum beverage can which makes it a sustainable product.

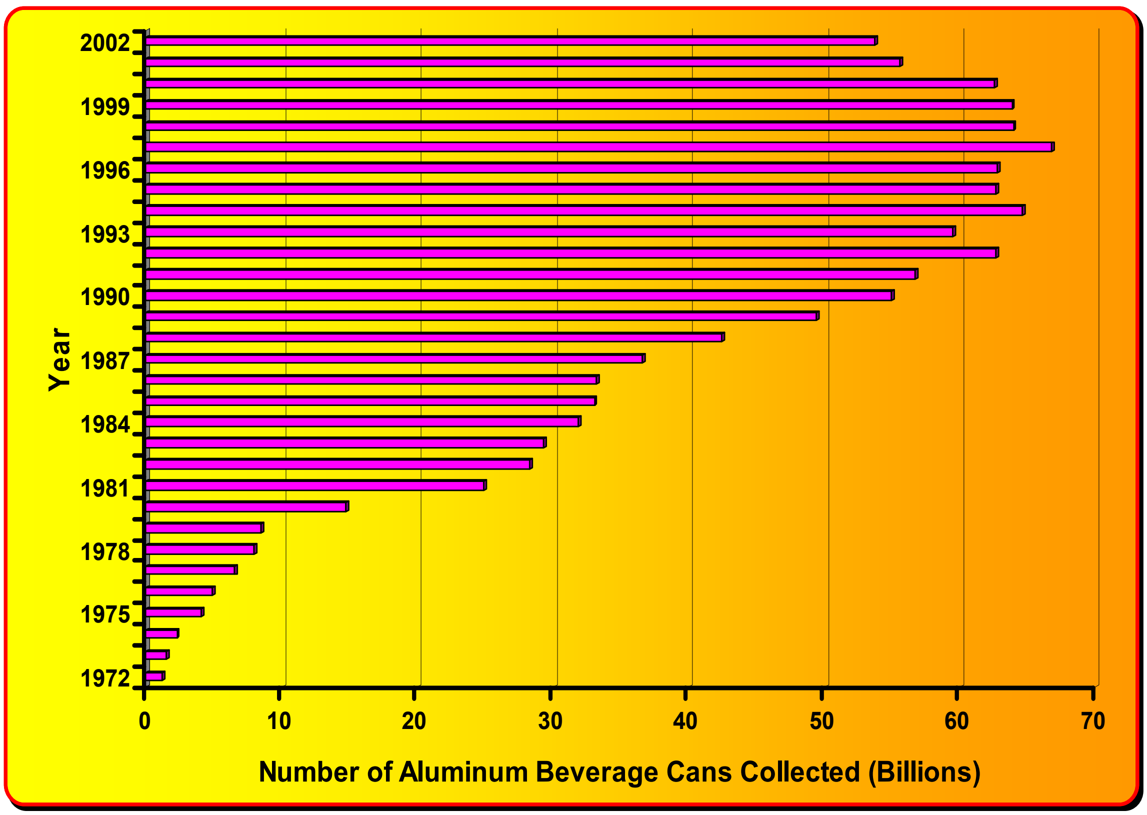

Figure 3.13: Number of Aluminum Beverage Cans Collected in the US for Recycling (Data The Aluminum Association Inc., Can Manufacturers Institute, Institute of Scrap Recycling Industries, Inc.)

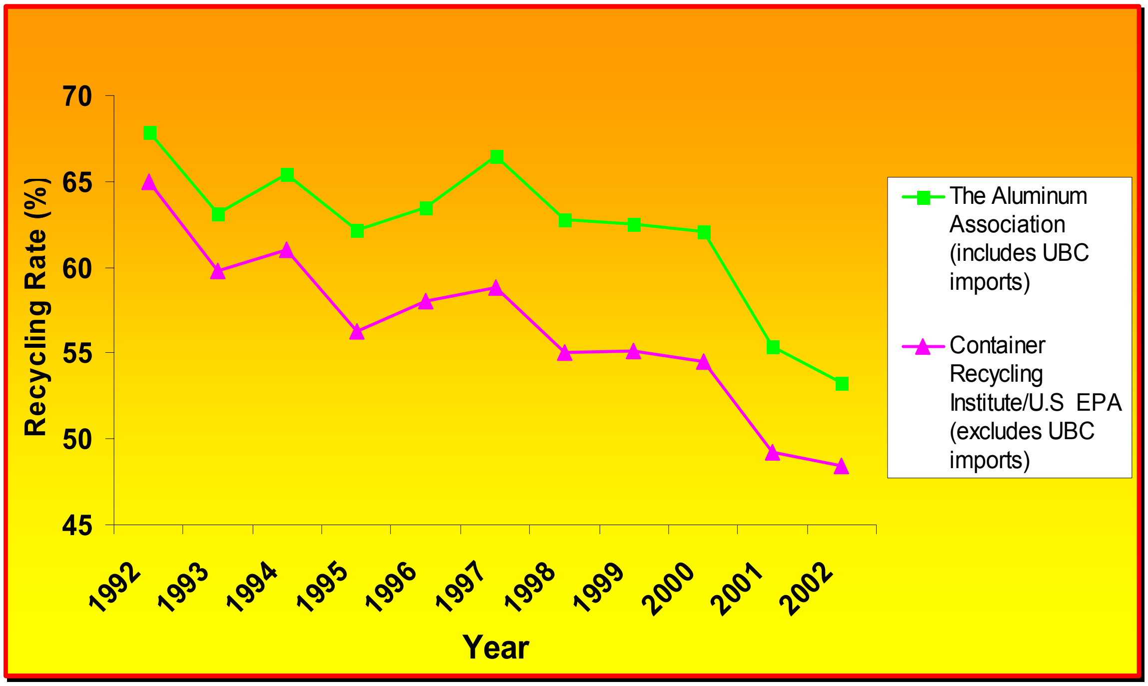

Figure 3.14: Aluminum Beverage Can Recycling Rate in the US (Data from The Aluminum Association Inc. and US Department of Commerce)

Arguments can be made that the recycling rate has been on the decline primarily because of the lower demand for aluminum beverage cans. However, Figure 3.15 proves otherwise. From 1972 to 2002, it has been shown that market demand for aluminum beverage cans has always been on the uptrend, hovering about 100 billion cans shipped per year today. Therefore, there is a fundamental problem in the declining rate of aluminum beverage can recycling in the US. It may be consumer's lack of awareness, lack of effort on government's part to educate the society of the benefits of recycling or even the lack of regulations enforcing recycling to a certain degree. Whatever the reasons are, the fact is aluminum beverage can recycling is declining in the US and although the market demand is still going strong, this is not sustainable as wastes is increasing.

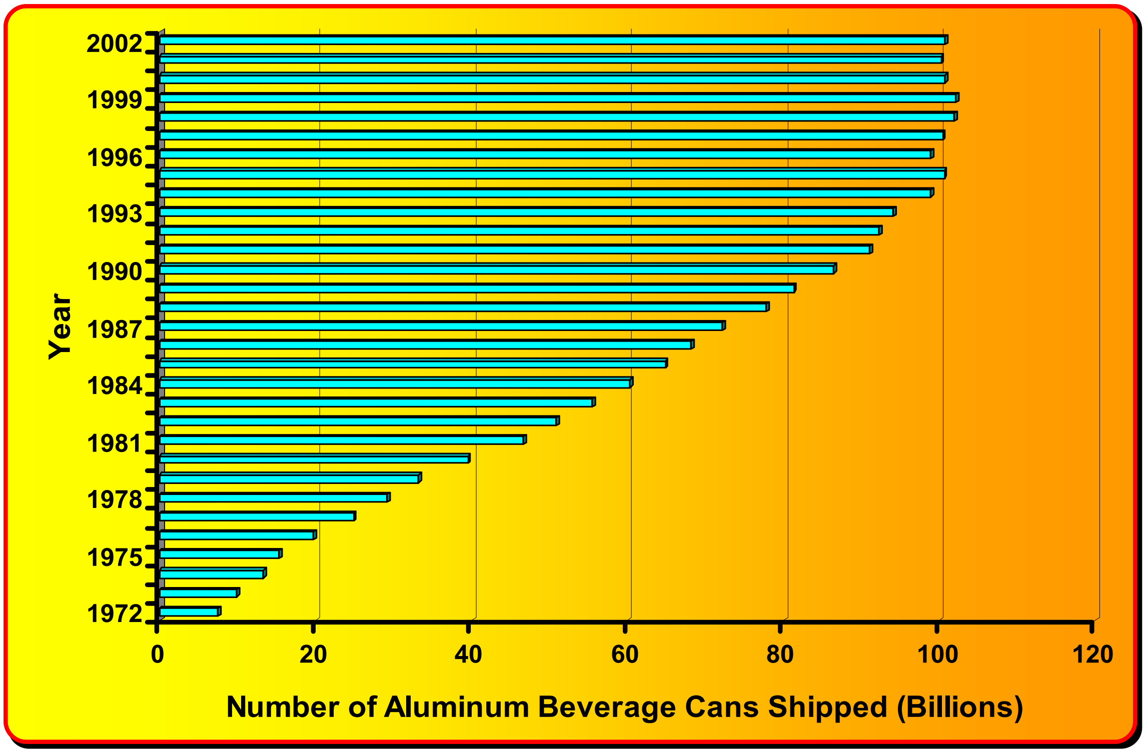

Figure 3.15: Number of Aluminum Beverage Cans Shipped in the US (Data The Aluminum Association Inc., Can Manufacturers Institute, Institute of Scrap Recycling Industries, Inc.)

United States used to be the world's largest primary aluminum producers. However, due to the higher energy costs in the US, primary production of aluminum has shifted to countries such as China and Australia [38]. Therefore, in order to satisfy domestic industrial needs of aluminum, the US had to import aluminum from those countries that are the primary producers. Not only that, some used beverage cans (UBCs) are also exported from the US to be recycled abroad. This means that the US has to rely on importing of aluminum from abroad to sustain its economy. This scenario does not make sense at all, since the US has the largest consumption of aluminum products, especially aluminum beverage cans. These aluminum products have the potential to be recycled but instead they go into the waste stream, and for the aluminum beverage can, only about 50% of the can is recovered to be recycled.

Statistics aside, over the past few years, manufacturers have been trying to bring product innovations into the can industry and some even tried to stray away from the traditional can design and tried to market aluminum bottle can (Figure 3.16) [39]. Although the aluminum bottle can is an exciting idea that offers fresh product aesthetics and has been a major hit in Japan, the US introduction is just beginning. One major disadvantage of the product is its relatively high manufacturing costs, but this will change with economy of scale. However, the traditional "beer tumbler" shaped aluminum beverage can still hold a special place in the hearts of consumer and is likely to stay for a long time. Other innovations that have been brought in and should be brought into the market are using aluminum beverage cans to market wine, milk and juice, self warming and cooling cans, temperature sensitive paints used on aluminum beverage cans and cans that inject nitrogen gas into the drink upon tab opening to make it more bubbly.

Figure 3.16: Aluminum Bottle Can [39]

However, from the discussion, it seems that in the US today, recyclability is still the main factor affecting aluminum beverage can's sustainability. Therefore innovations have to be made to the product design to enhance its sustainability, especially in recyclability. There are many ways to enhance a product's sustainability, and it can be done through the system's or process perspectives. However, in the next chapters, we will discuss why the product's point of view is chosen and a new methodology for sustainable product design is developed and implemented towards creating a new aluminum beverage can design.

Chapter 4

Design for Sustainability

As pointed out in earlier chapters, one inadequacy with the current sustainable product design methodology is that only one product life-cycle is considered. Traditional notion holds that a product's life-cycle ends when it is thrown away and after recycling, the product starts a brand new life-cycle. The idea of a product having multiple and even perpetual life-cycles is alien to many and new. However, a truly sustainable product needs to have multiple and perpetual life-cycles with a closed loop material flow. This research also focuses on developing a sustainable product from the product's point of view. In looking from the perspectives of the product level, product designers are working within the constraints of the current infrastructure, be it manufacturing, distribution or recycling. Therefore, the introduction of a new sustainable product does not require huge upfront costs to change the current manufacturing, distribution or recycling infrastructure to accommodate the product. A new sustainable product should be a product of pure engineering innovations that improves its economical, environmental and societal value without requiring a systems change.

4.1 Design for Sustainability Methodology

Most design methodologies are created either to overcome deficiencies in the current design and manufacturing processes, or to improve the recovery and recyclability of the products during and at the end of its service life. Overcoming the deficiencies in the design and manufacturing processes may include reducing energy, material and labor costs, as well as, reducing wastes in machine utilization and material flow. Some of the traditional design methodologies are also utilized to produce products that are easier to be serviced, repaired, disassembled, recovered and recycled, while a comprehensive methodology to represent various major sustainability elements is yet to emerge.

However, if we look at the big picture, the desired outcomes of all those traditional design methodology points to one or more aspects of sustainability. In other words, most traditional design methodologies are created and utilized to enhance the products from either one of these three focal points; economy, environment and society. The final objective and outcomes of utilizing any of these traditional design methodologies would be trying to come up with some kind of a sustainable product. Therefore, if there was an “ideal sustainable product design methodology”, it would be the fusion of all the traditional design methodologies and its desired outcome will be a sustainable product; encompassing sustainable manufacture, recovery, recycle as well as being environmentally friendly and benefiting to society, fulfilling all three pillars of sustainability; environment, economy and society. This “ideal sustainable product design methodology” should be called Design for Sustainability (DFS). Figure 4.1 shows the major elements of DFS which consists of all the other traditional design methodologies. All outcomes and objectives of those design methodologies point towards the requirements of DFS. The ideal design for sustainability methodology should fulfill all three important elements in sustainable development without compromising any of them. In addition, DFS should have the notion that the life-cycle of a sustainable product should be considered as multiple and perpetual, where the base material keeps flowing after the recycle stage.

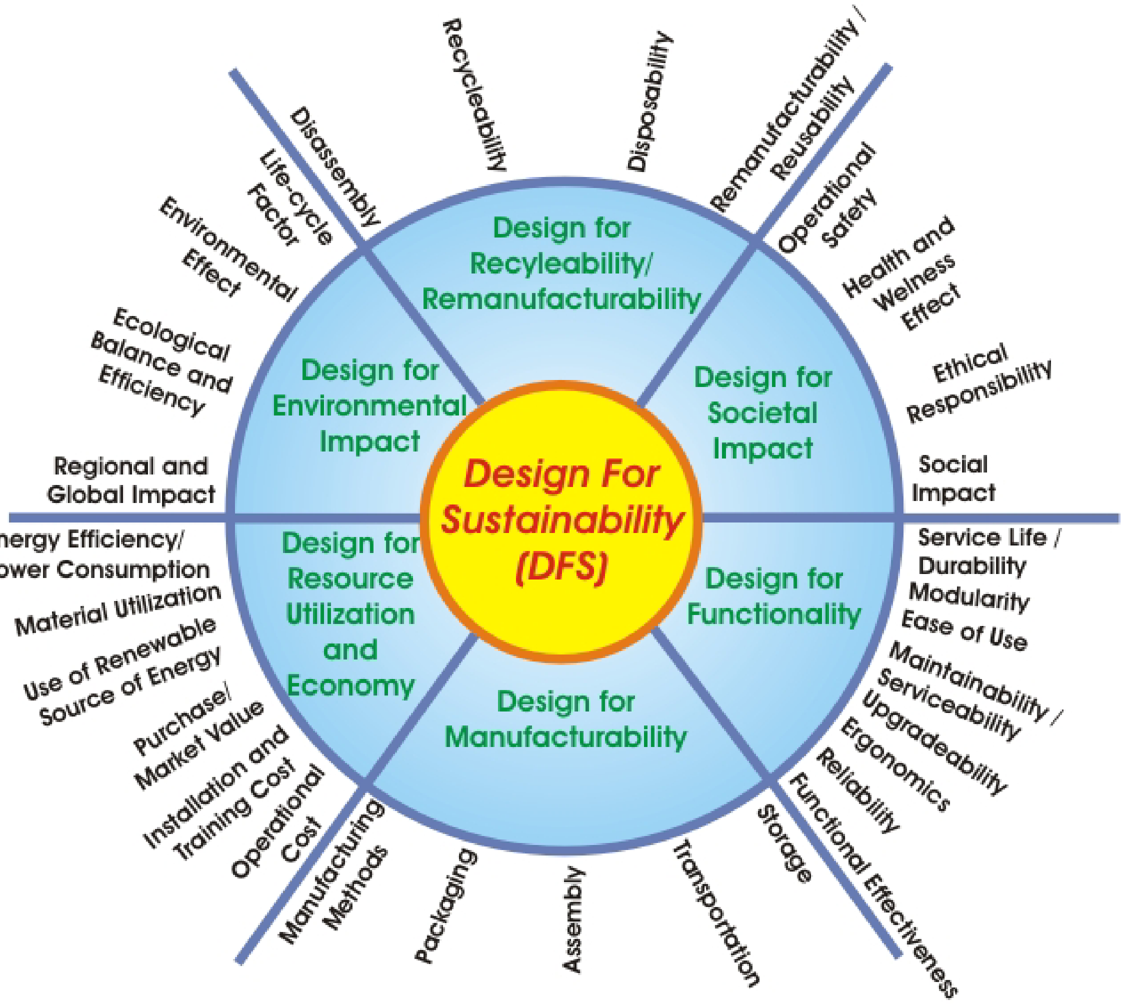

Figure 4.1: Major Elements Contributing to Design for Sustainability.

4.2 6R Concept: Multiple and Perpetual Material Flow

From the marketing and business perspectives, a product's life-cycle is usually defined as the progress of the product through introduction, growth, maturity and decline stages. Engineers define product life-cycle assessment

(LCA) as an objective process to evaluate the environmental burden associated with a product by identifying and quantifying energy, material uses and releases on the environment, and to evaluate and implement opportunities to affect environmental improvements [40]. This assessment usually includes the entire life-cycle of the product, encompassing extracting and processing of raw materials; manufacturing, transportation, and distribution; use/re-use/maintenance; recycling; and final disposal of the product [40]. However, this definition and assessment methodology only consider the product as having a single life-cycle, and no consideration of perpetual material flow for sustainability is prevalent.

The first step in developing an ideal design for sustainability methodology for producing a truly sustainable product is ensuring that both the design methodology and the life-cycle evaluation of the finished product include an element of multiple life products with perpetual material flow. Traditionally, the life-cycle of a finished product with a single life-cycle starts from manufacture and ends with disassembly and/or recycling. The recently introduced 3R approach to manufacturing (Reduce, Reuse, Recycle) appears to be in line with this, while multiple and even perpetual life-cycle approach would seem essential for a fully sustainable product. An effort to model a product's life-cycle by considering the perpetuality of material flow is shown in Figure 4.2, typically for automobiles.

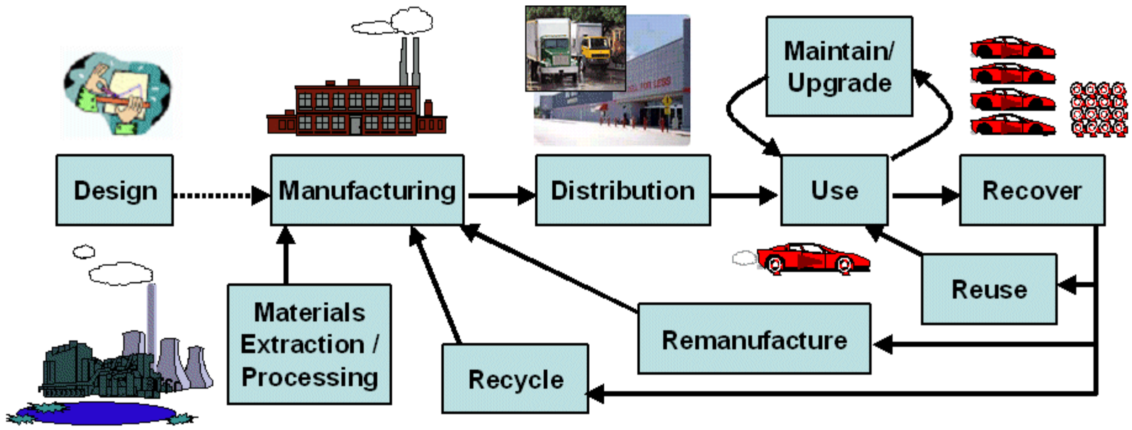

Figure 4.2: Automobile life-cycle (Adapted from [41])

In designing for sustainability to maintain perpetuality of material flow, the raw material used to manufacture the initial product is expected to be recovered and recycled at the end of the first life-cycle before "flowing" into the next life-cycle as part of another product. This multiple and perpetual life-cycle concept is defined by the 6R concept as shown in Figure 4.3. There are 6 integral elements in the 6R concept; Recover, Reuse, Recycle, Redesign, Reduce and Remanufacture. Each integral element by itself forms the basis for sustainability. The first stage in manufacturing a product begins with designing. In this initial step, companies look at the market and competitor's product in order to design a product that fits the consumers' needs, able to compete with the competitors offering and environmentally friendly. This is done by evaluating the product's sustainable elements, such as functionality, manufacturing costs, serviceability, recycleability, etc. After this impact analysis has been done, the product will go into production and be sold to consumer for use. According to the 6R concept, when the product has no more value or use to the first owner, instead of going directly to be recycled, it needs to be recovered. In this Recover stage, the product is stripped down and useful parts are salvaged as spare parts for identical products while the remaining presumably defective materials are sent to be recycled. An example of this process can be found in the automotive industry. Daily, hundreds of used and "totaled" vehicles are stripped apart to salvage spare parts and the rest of the automobile is sent to be scraped and recycled. In addition, many ink cartridges for printers are recovered by manufacturers, refilled and sold as brand new ink cartridges.

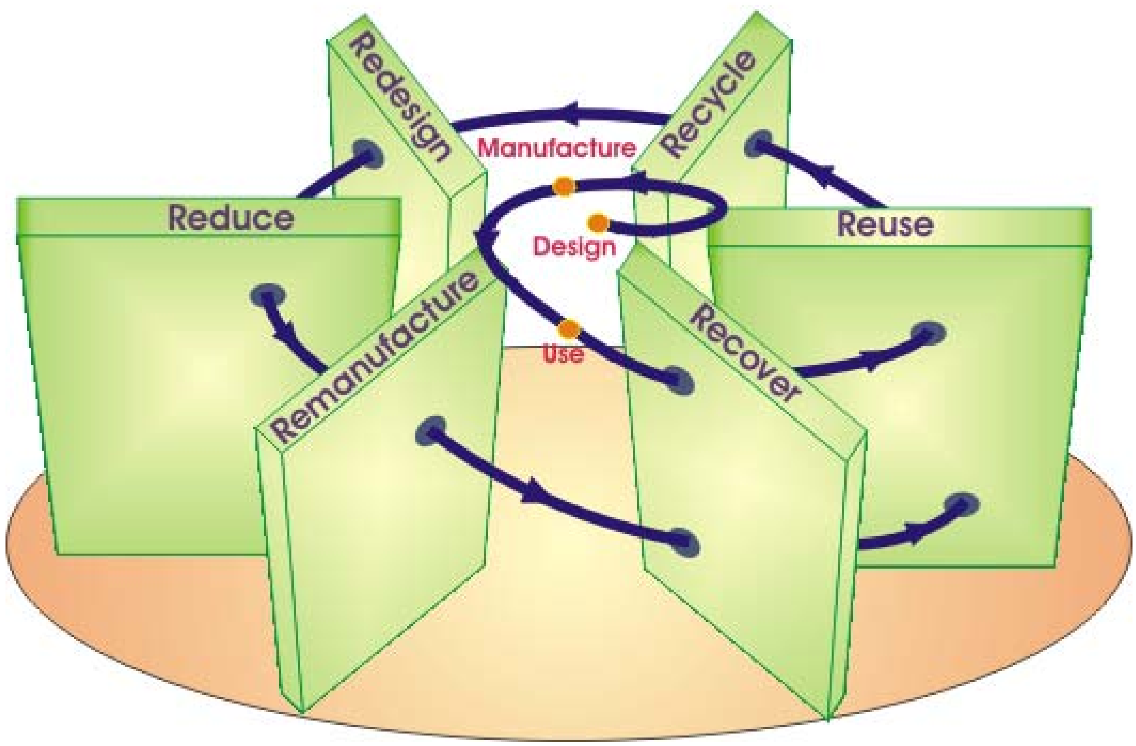

Figure 4.3: Stages of material flow in perpetual product life-cycle involving 6R elements.

These salvaged parts from the Recover stage are then used in other products. This next stage is the Reuse stage. After the usefulness of the parts is exhausted completely, it goes to the Recycle stage. Usually, this is the end of life for a single life-cycle product. However, in order for a product to have multiple and even perpetual life, we have to consider the “flow” of materials from the previous product into the new product, and take this as the continuation of the product’s life. In the next stage, instead of making the same product again, a sustainability-minded designer will redesign the product again to make it more economical, environmentally friendly and fulfill the needs of society, all three aspects of sustainability.

This is what we call the Redesign stage. During the redesigning process, reducing the materials used in the product, the manufacturing processes, and so on, is critical in order to bring the product to the next level of sustainability and to make it competitive in the market. This stage is the Reduce stage. After all of this is completed, the product is remanufactured again as a similar product but with enhanced sustainability elements. The cycle is repeated again as shown in Figure 4.3. The 6R concept is unique in the sense that it promotes the idea of Kaizen, or continuous improvements in product design, that benefits the environment, economy and society. In addition, the concept can be tailored to suit any specific product. The priority for each stage in the concept is different with different product, for example the recovering of aluminum beverage cans for reuse as “spare parts”, analogous to the spare parts recovery in the automotive industry, is not a priority, although it can be recovered and used in crafts. Therefore, the Reuse stage can be skipped and move to the next stage, Recycle.

This flexibility in the concept makes it applicable to a wide range of products, although a truly sustainable product should ideally "flow" through each stage.

4.3 Certified Sustainable Product

As discussed earlier, a truly sustainable product should "flow" through each of the stages in the 6R concept. As seen in Chapter 1, most existing sustainable product design methodologies only have the stereotypical notion that a sustainable product should be "green". This stereotype is not at all beneficial, as businesses are not much interested in a "green" product that can not generate sales or profit. Neither does the idea that a sustainable product should put the environment first and consider the societal impact as second hand considerations makes any sense. We should not assess sustainability from "pure ecology' point of view [42], rather look at sustainability from three equal perspectives; environment, economy and society. A sustainable product should not be assessed as having only a single life-cycle, but should be treated as having multiple and perpetual life-cycle.

The mindset of sustainable product being a "green" product is not wrong, just inadequate and incomplete. The idea of sustainability and sustainable products would be fully accomplished only if the three pillars of the idea; environment, economy and society are placed on the same level, with multiple and perpetual life-cycle considerations built into the product. The 6R concept is a useful tool in sustainable product design, and we will apply this tool to the aluminum beverage can to enhance its sustainability, especially its recyclability.

As shown in Chapter 3, the recycling of aluminum is not only the strongest point of the aluminum industry, but the recycling of aluminum beverage cans has been on the decline over the past few years compared to the other aluminum products (see Figure 3.8 in Chapter 3). Therefore, the recyclability of aluminum beverage cans is the "silver bullet" in sustaining the aluminum beverage can in the US market. Increasing the recyclability of the can not only benefits the environment by reducing waste, but also improves economic profits for the industry (recycled metal costs less than the primary metal) and provides jobs to the community (societal benefits). For this reason alone, the aluminum beverage can should not be considered "recyclable" but "certified sustainable product" (Figure 4.4), satisfying six integral elements of product sustainability discussed previously.

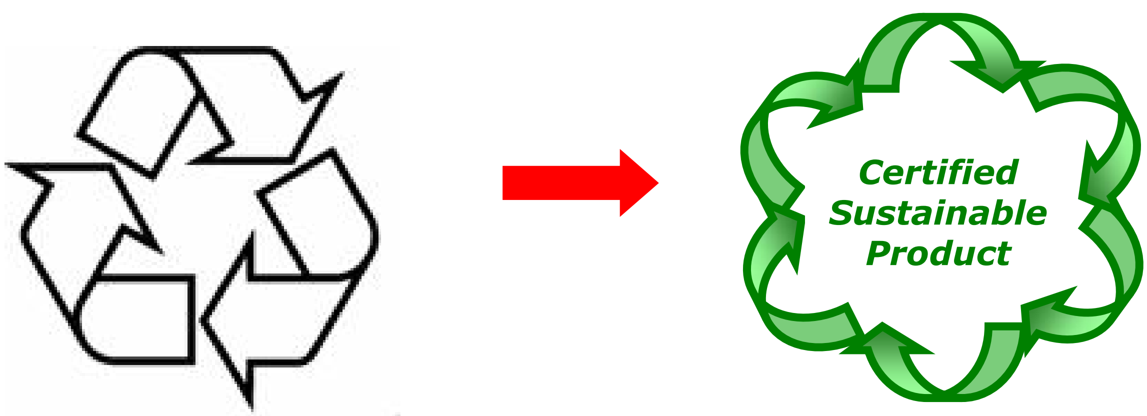

Figure 4.4: The Proposed Sustainability Enhancement in Aluminum Beverage Can (From recyclable product to certified sustainable product)

Chapter 5

Innovative Aluminum Beverage Cans Design for Increased Recylability

After detailed analysis on the overall status of the product sustainability in the aluminum industry, especially in the aluminum beverage can market; we have arrived at a conclusion that the recyclability of the aluminum beverage can is the strongest sustainability point of the product. Not only recycling of the aluminum beverage can profitable to the environment, but also it is beneficial to the economy and the society dimension. In addition, we established that in order to enhance the sustainability of the aluminum beverage can, we need to work from the product's perspectives with the current manufacturing and recycling constraints. The systems impact down the line will also be assessed. The 6R concept will be applied to this task.

5.1 6R Concept applied to New Innovative Aluminum Can Design

The redesign of the aluminum beverage can will not be done from the ground up by looking at the existing design and bring subtle innovations with huge impacts into the product. We will apply the 6R concept to the 12 oz can, which is the workhorse size of the aluminum beverage can industry and accounts for over 90% of all aluminum beverage cans manufactured in the United States. The aluminum beverage can is a well developed and mature product, and from the product design point of view, it has some good features. First is the stay-on-lid, second is the cylindrical shape of the body for optimal load distributions, as well as the dome-shaped surface at the bottom for better stackability and internal pressure distribution. The only sustainability disadvantage of the can is the dual alloy construction. The lid is currently made out of a stronger alloy because it needs to withstand top loads during stacking and also be able to be double-seamed. This requires that the two alloys be separated during recycling and melted in two separate lines of furnaces. Therefore it seems obvious that the new innovative aluminum beverage can should be engineered to be manufactured out of only one alloy while retaining rest of the efficient current design features.

There are six stages of material flow in the 6R concept; Recover, Reuse, Recycle, Redesign, Reduce and Recycle. Of these 6 stages of material flow, we have identified that 3 stages, Redesign, Reduce and Recycle, are crucial to the aluminum beverage cans and should be used for the product redesign. The process of enhancing the sustainability of aluminum beverage cans begins with a new design concept from the Redesign stage in the 6R concept. Significant changes in the current can designs are not desirable according to the principles of sustainability; because a completely different can design would require major revamping of the manufacturing processes involving large monetary costs, thus not economically sustainable. Therefore, subtle innovations to the current design that produce major impacts to the recyclability of the aluminum beverage can are desired. In addition, this innovative can redesign should also take into account what is needed in the next Reduce stage. In other words, the redesigning of the can not only means coming out with a design that is different in terms of looks and functionality, but also trying to reduce the recycling steps or materials used to manufacture the cans. Finally, the new aluminum beverage can should have a better performance in the Recycle stage compared to the current design.

The concept for the proposed new and innovative design is based on a can made of out a single alloy AL3004. This means that instead of manufacturing the lid out of AL5182, it can be made out of AL3004, the same alloy as for the body. In order to compensate for the weaker AL3004, the lid will have a concave shape to withstand and distribute loadings better. This also actually improves its stackability as the concaved lid complements the dome-shaped bottom of the body. The design and performance evaluations of the new unialloy can will be described in the next section.

5.2 Finite Element Analysis of New Unialloy Can Design

The design inspiration for the new unialloy aluminum beverage can comes from the idea that a curved surface would be stronger than a flat surface, in terms of the ability to distribute stresses better. The left can in Figure 5.1 shows a radical can design with an extremely concave lid. However, overly curvaceous lid would make opening the tab harder, as well as not aesthetically appealing. However, if we refined down this idea further, we arrive at the can design shown on the right in Figure 5.1. At fist glance, this new design would seem similar to the current existing design which is shown the center of Figure 5.1. However, upon further inspection, we notice a slightly curved lid in the new design on the right. The curvature of this lid is only 6 cm with the center point of the curve about 3 cm from the bottom, thus is barely noticeable. This slight curvature is more pleasing to the eyes than the can on the left in Figure 5.1, and would be no different than the current design to open with a tab as the curvature is slight. Also, this curved lid would complements the dome-shaped bottom of the can, thus further enhancing its stackability.

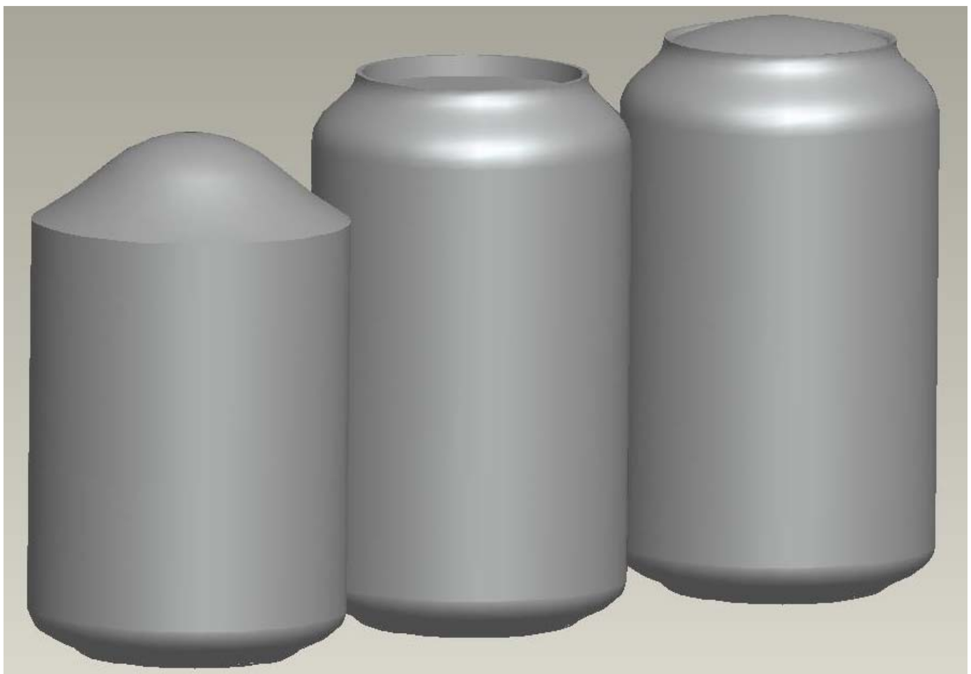

Figure 5.1: Aluminum Beverage Can Design (From left: Initial new inspiration, Current aluminum beverage can, Final New Unialloy Aluminum Beverage Can)

The structural performance of the unialloy aluminum beverage cans still needs to be assessed, with the current aluminum beverage can used as a benchmark. Attempts have been made previously to predict and model the structural performance of aluminum beverage cans [19] and simulate the manufacturing process of the can [43], using advanced CAD and FEM software. The cans are modeled in Pro/Engineer Wildfire with the exact dimension shown in Figure 2.8 in Chapter 2. The body shell thickness varies from 0.003 in (0.075 mm) to 0.012 in (0.3 mm), depending on the location, with the thickest portion near the bottom and the thinnest at the middle. The lid was measured using a micrometer caliper and the average thickness was found to be 0.027 in (0.687 mm). The current design and new unialloy design would share the exact same dimensions, with the exception of the 6 cm curvature on top of the lid.

The normal criteria to assess the structural performance of any beverage can design is that is has to be able to withstand internal gas pressure of 90 psi (620528.1561 Pa) and top load of 250 lbs (113.3981 kg). The cans were drawn as thin surfaces in Pro/Engineer Wildfire and using the built in Pro/Mechanical extension, the surfaces were modeled as shell elements with the appropriate alloy properties and thickness. Next, loadings of 90 psi uniform pressure internally and 250 lbs axial top load on the lid were applied to the cans. The lid and body seaming points are assumed as rigid. Next, the model was meshed, and imported into ANSYS 7.1 to be stress analyzed. The element used to represent the thin walled structure of the can is Shell 93. According to the ANSYS help files, SHELL93 is particularly well suited to model curved shells. The element has six degrees of freedom at each node: translations in the nodal x, y, and z directions and rotations about the nodal x, y, and z-axes. The deformation shapes are quadratic in both in-plane directions. The element has plasticity, stress stiffening, large deflection, and large strain capabilities. Figure 5.2 shows the 8-node Shell93 elements.

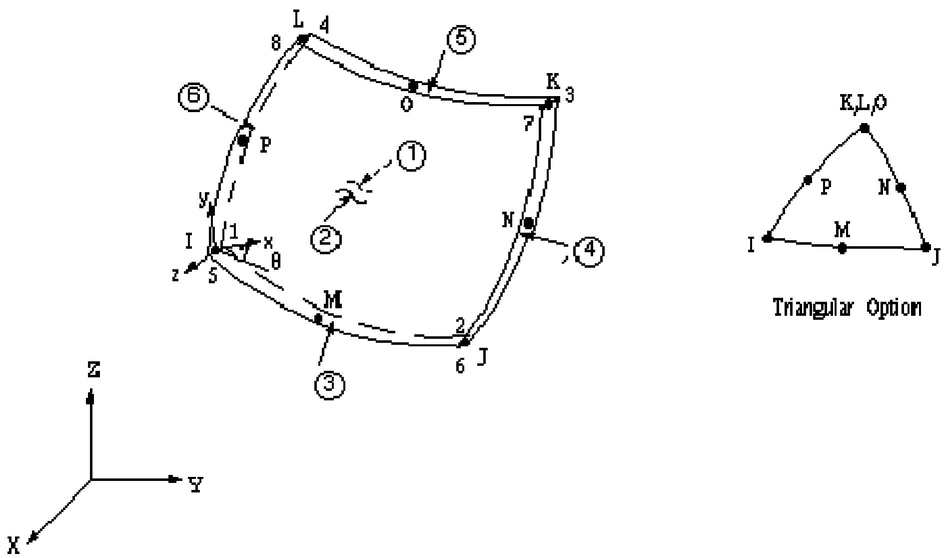

Figure 5.2: Shell93 8-Nodel Structural Shell (From ANSYS 7.1 Help Files)

ANSYS results for both cans are shown in Figure 5.3 to 5.10. The maximum stress for both can designs is 336 MPa, with maximum axial displacements of 0.677 mm for the current can design, and 0.350 mm for the new unialloy design. This analysis shows that both designs hold up pretty well and are quite similar in performance. Maximum stress does not occur on the lid for both cases. If we look at Figure 5.6 and 5.10, the analysis shows a better load distribution for the unialloy can with curved surface than for the present can. The function of Pro/Engineer, Pro/Mechanica and ANSYS is to show a relative structural comparison between the two can designs. The results obtained are as close as possible to real world performance with minimal margins or error. The main significance of this analysis is to show that comparable performance can be obtained by using a unialloy can construction made out of AL3004.

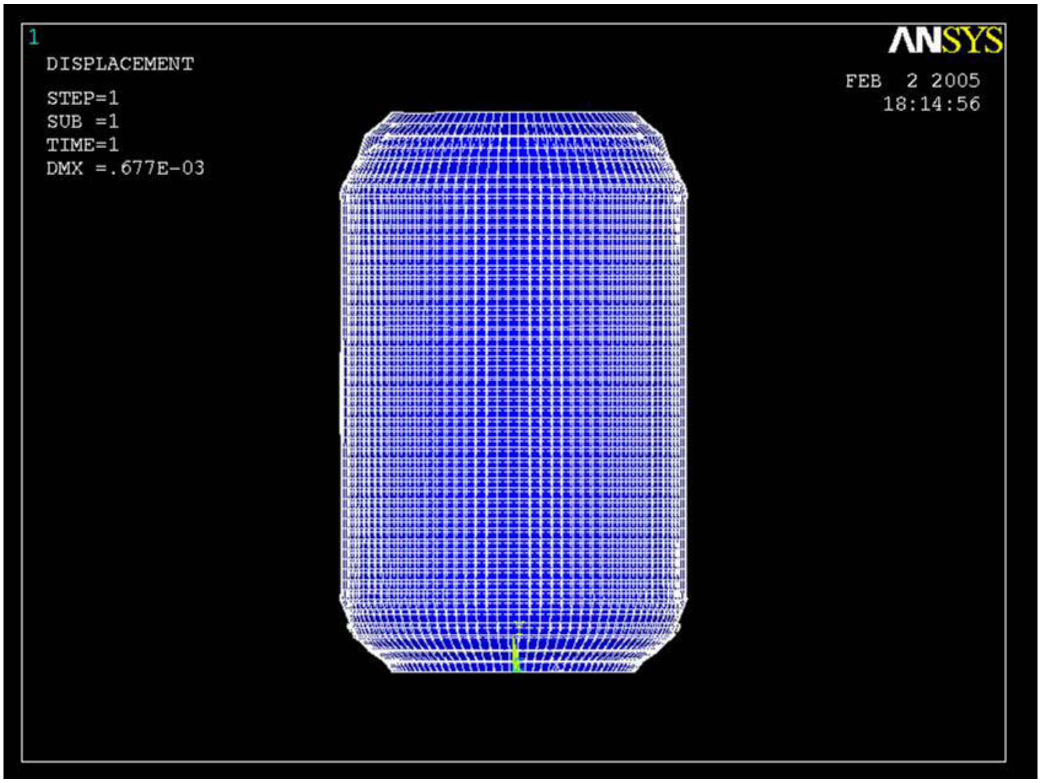

Figure 5.3: Current Can Displacement Subjected to Loads

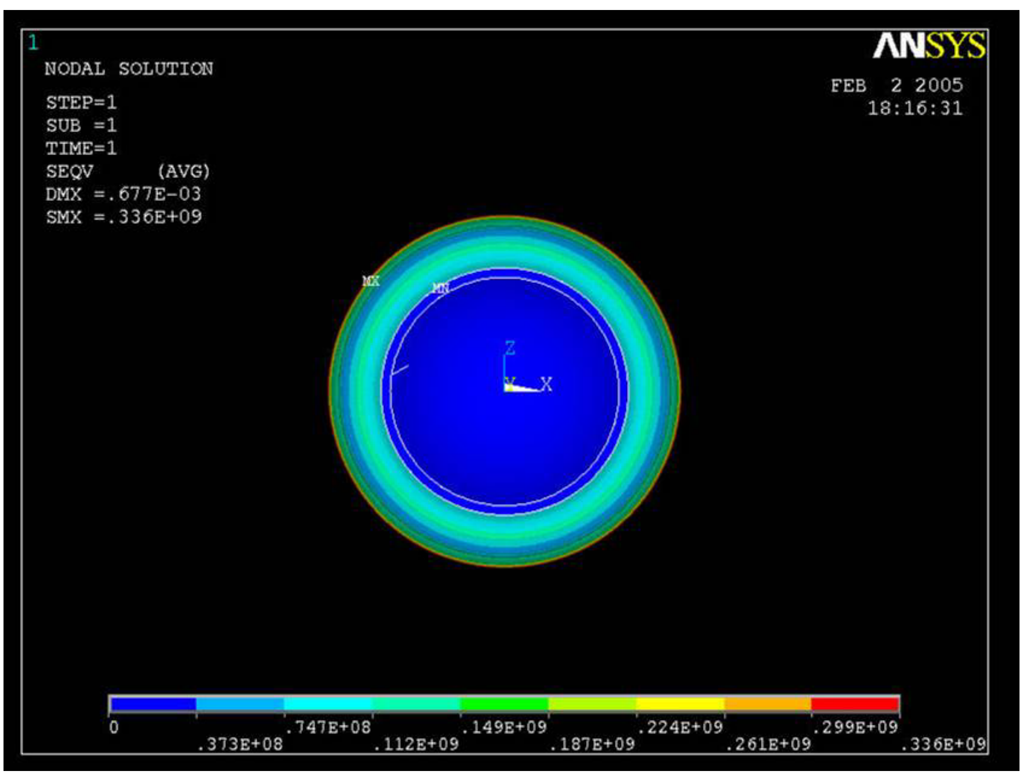

Figure 5.4: Current Can Stress Distribution Subjected to Loads (Bottom view)

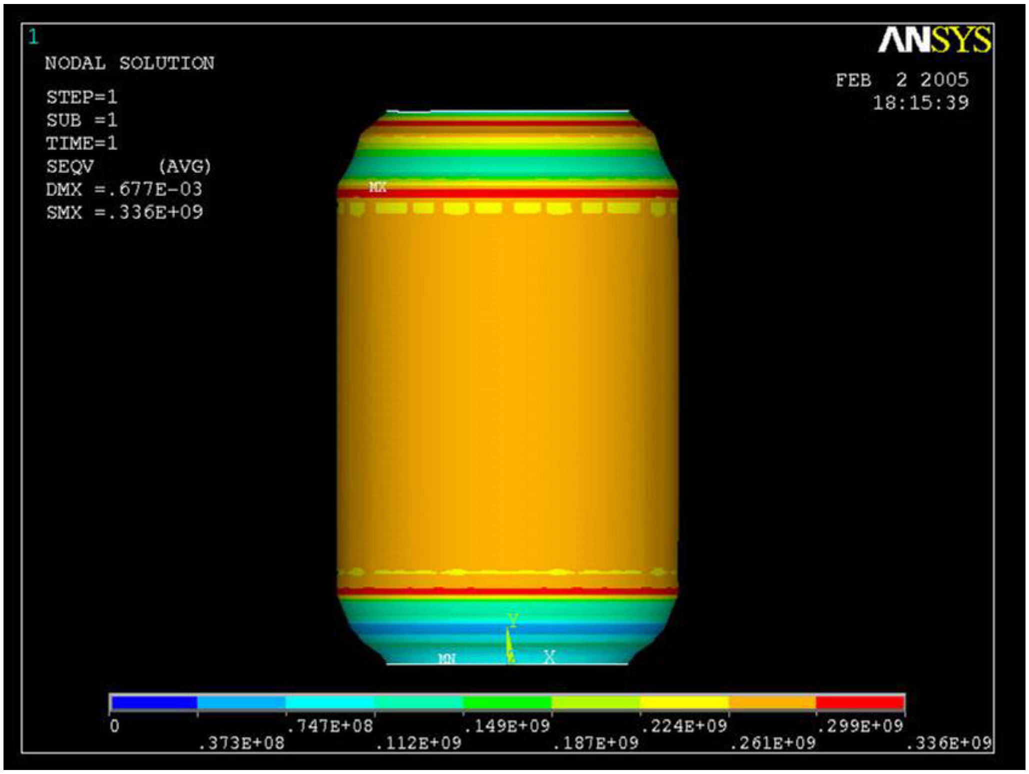

Figure 5.5: Current Can Stress Distribution Subjected to Loads (Front view)

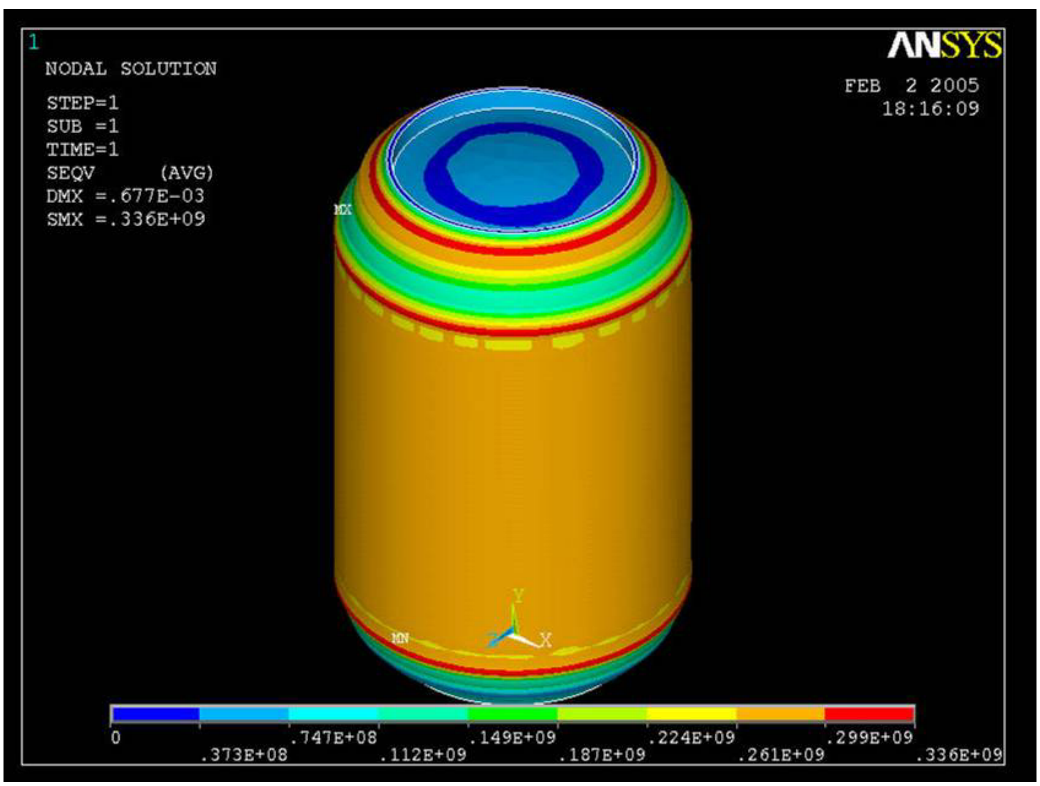

Figure 5.6: Current Can Stress Distribution Subjected to Loads (ISO view)

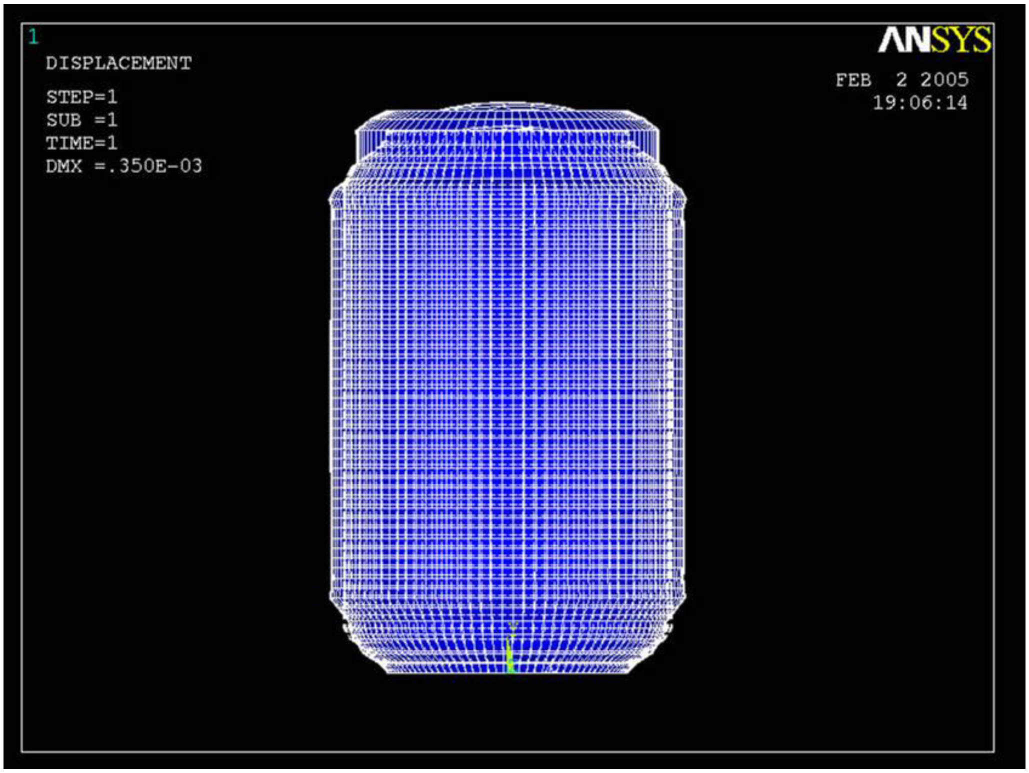

Figure 5.7: Unialloy Can Displacement Subjected to Loads

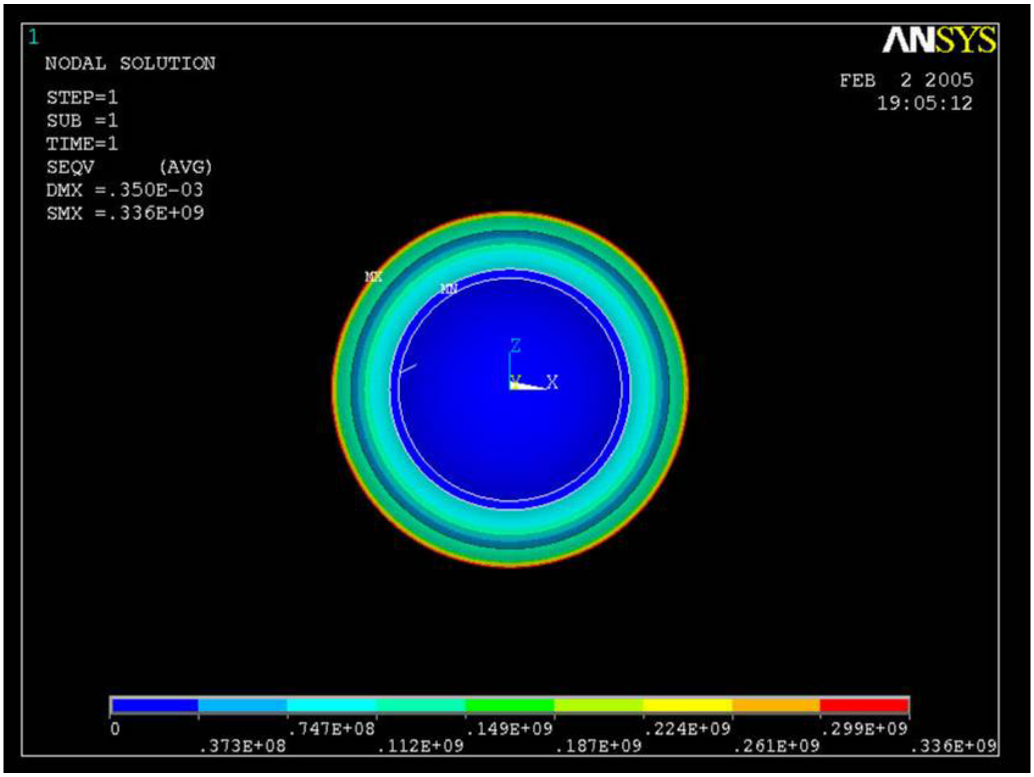

Figure 5.8: Unialloy Can Stress Distribution Subjected to Loads (Bottom view)

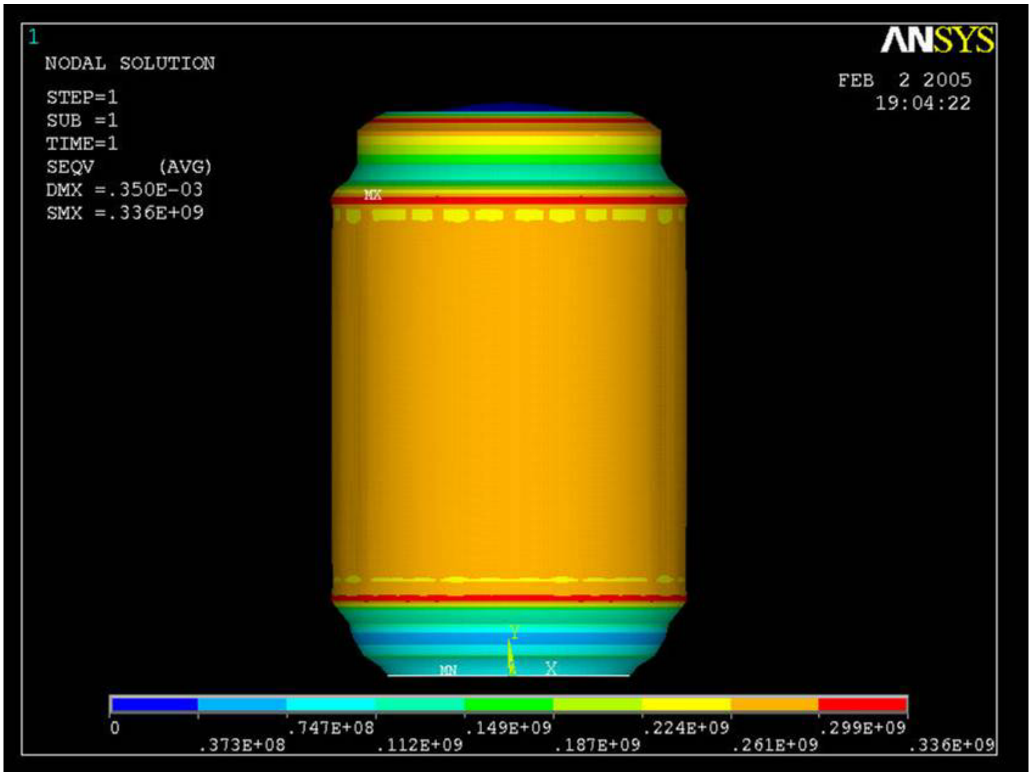

Figure 5.9: Unialloy Can Stress Distribution Subjected to Loads (Front view)

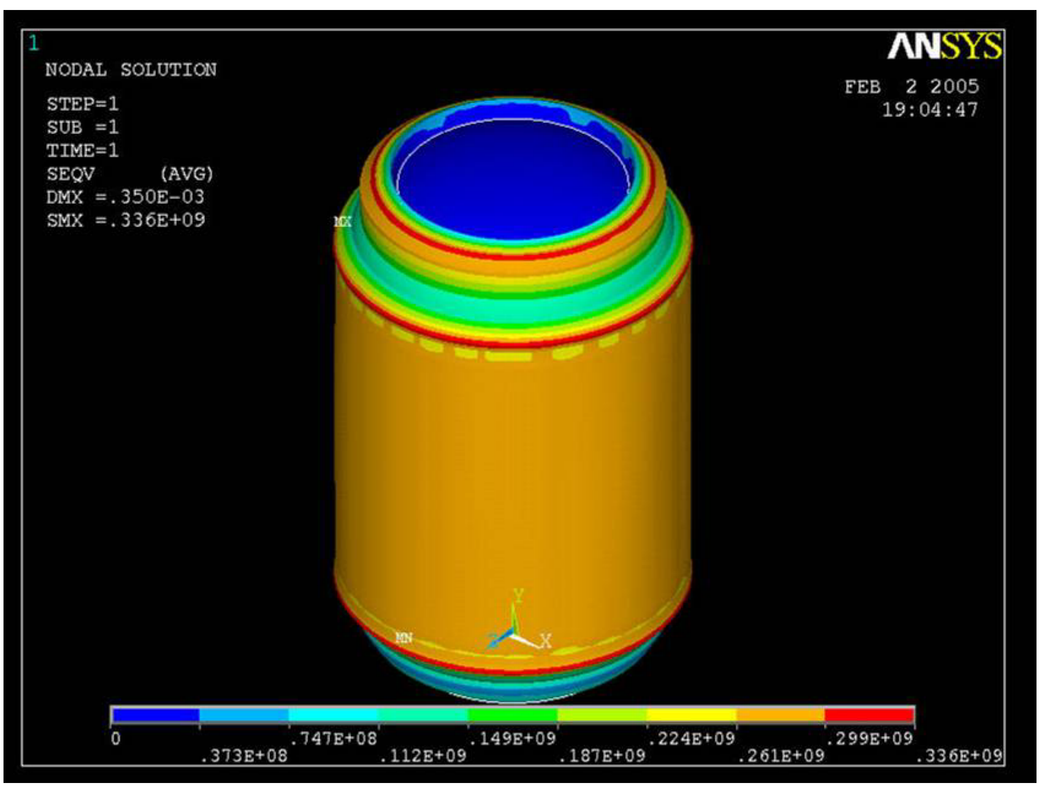

Figure 5.10: Unialloy Can Stress Distribution Subjected to Loads (ISO view)

5.3 Impact of New Unialloy Aluminum Beverage Can Design

Our main objectives in enhancing the sustainability of the aluminum beverage can, through the product's point of view, is based upon the consideration that redesigning the product under the constraints of the existing manufacturing, distribution and recycling infrastructure would be more sustainable redesigning from the systems perspectives as it would not incur huge changes in the current infrastructure, thus making economical sense as well. However, changes at the product level would lead to huge impact at the systems level.

One obvious impact of the unialloy can at the systems level is on recycling. The unialloy can would revolutionize the recycling process, and further increasing the economical viability of the process. By eliminating the need for separation and melting in two separate lines of furnaces, energy consumption is reduced and emissions from recycling such as green house gases are also minimized. A cheaper way to recycle would encourage the industry to expand thus employing more workers. The impact of the unialloy can would therefore be threefold, in terms of environment, economy and society.

Chapter Six

Unialloy Aluminum Beverage Can Recycling

In this chapter we will quantify the recyclability of both the current can and the new unialloy can. Flowcharts of the recycling processes will be analyzed and based on published works, we will try to model the effectiveness of the recycling process for both aluminum beverage cans.

6.1 Unialloy Aluminum Beverage Can Recycling Process Modeling

The aluminum beverage can recycling process was discussed in Chapter 2 and Figure 2.12 shows a very good illustration of the process. It is obvious that if we have unialloy aluminum beverage can, the process would be much simpler. The proposed recycling process for the unialloy can is shown in Figure 6.1. From [22-23], it is known that melting aluminum alloys in the furnace typically would produce significant amount of “skim”, the mixture of metal, oxides, other contaminants and trapped gas that floats on top of the melt [22]. This mixture is typically about 15% of the original melt from both AL3004 and AL5182. The recovery of metal from this melt is only about 6-8% of the original melt. This means about 7-9% of the original melt will be lost forever. The recovered metal can only be used in body stock manufacturing because of its high manganese and contaminant level [22-23]. In order to balance the recycling closed-loop process, some metal from the potroom may need to be injected into the recycling flow. The process percentage typically depends on the melt loss. During the casting and rolling of the recycled alloys into either body or lid sheet, about 42%

of the weight of the original melt would be shaved, cropped or slit off in various stages [22-23]. Typically, the recovering of this scrap on the production line would not be 100%, thus, some percentage of this, about 42% would be loss. If the ratio of lid to body is approximated to be 0.2, then 20% of the various losses and scraps are generated by the lid. Figure 6.2 and 6.3 shows the flow chart of the dual alloy and unialloy aluminum beverage can recycling process respectively.

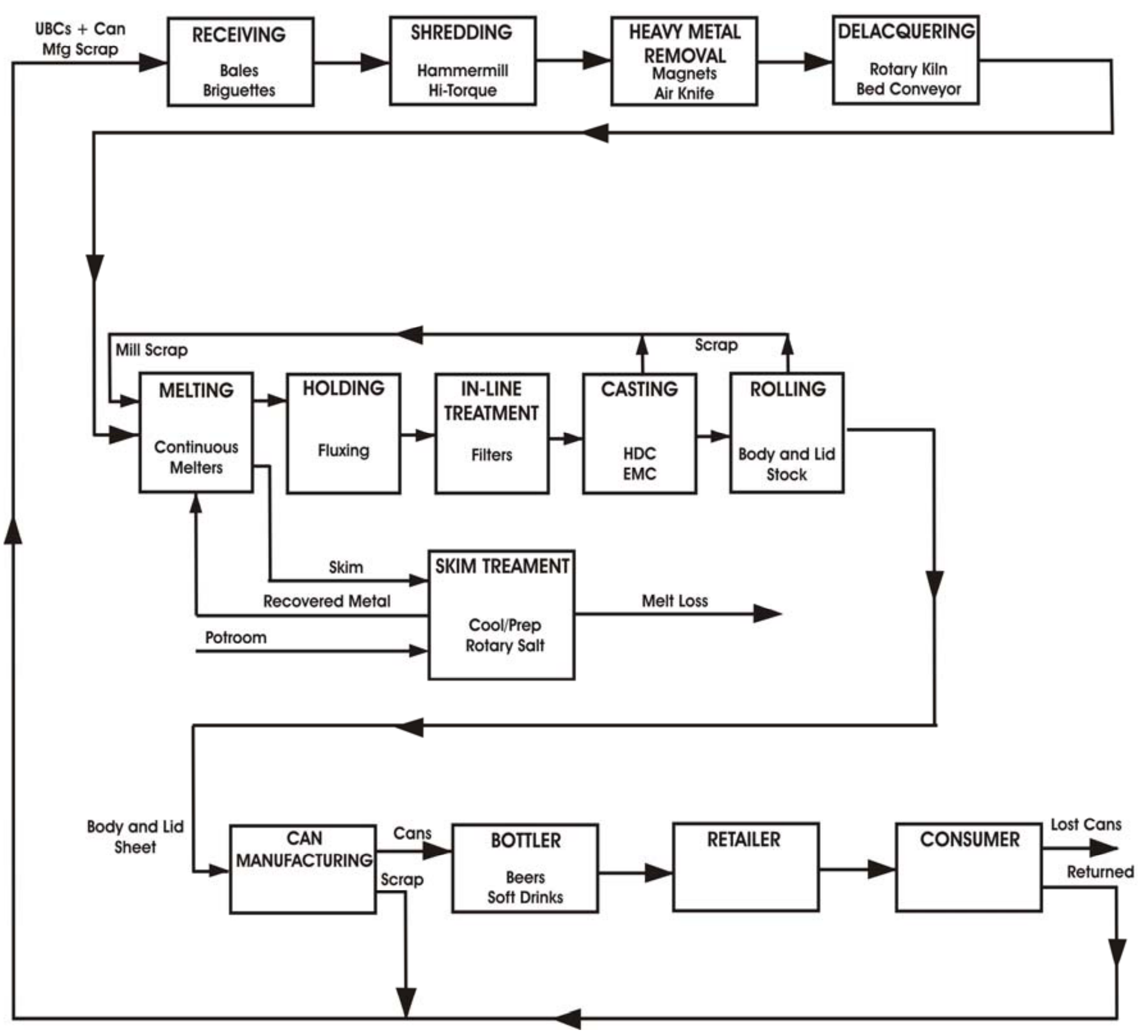

Figure 6.1: Unialloy Aluminum Beverage Can Recycling Process.

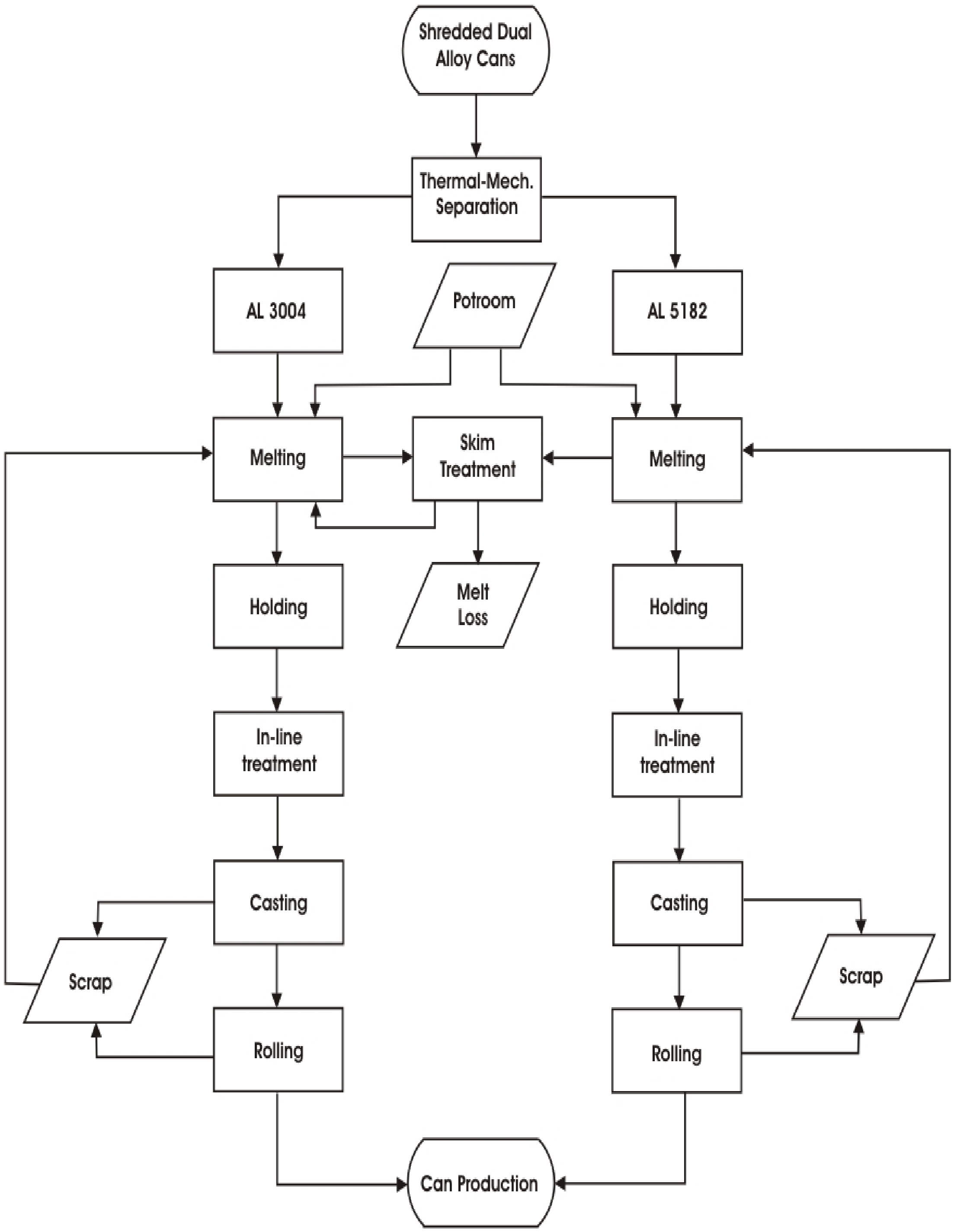

Figure 6.2: Dual alloy Aluminum Beverage Can Recycling Process Flow Chart.

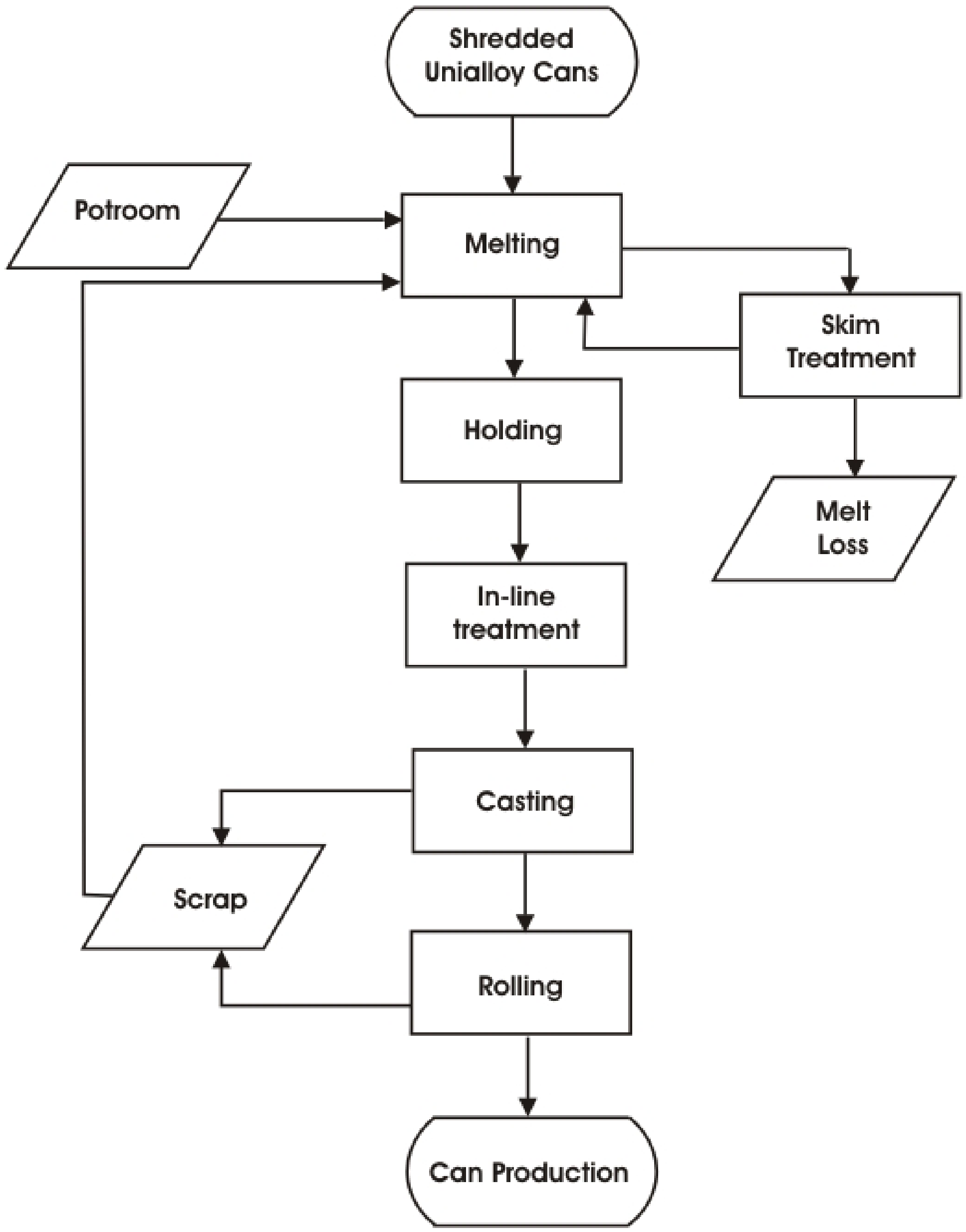

Figure 6.3 Unialloy Aluminum Beverage Can Recycling Process Flow Chart.

We will now compare the recycling efficiency of both the current can the unialloy can. If we use the lid to body ratio of 0.2, from [22-23], we can imply that melting process of the AL3004 would produce 12% skim and melting of AL5182 would result in 3% skim. If the skim recovery process recovers 7% of the original melt, then the remaining 8% skim would be melt loss. Because of the fact that metal from the potroom would need to be injected into the closed-loop process to balance the material flow and also the recovered skim can only be used for body manufacturing in dual alloy can, then 5% and 3% of the original melt's metal would need to be injected in the AL3004 and AL5182 line respectively. For the unialloy beverage can, since it is made out of AL3004 only, then skim formation would only be 12% of the original melt. Skim recovery stays the same at 7%, the melt loss would be 5%, meaning 5% metal from the potroom would be needed to compensate the cycle.

The following equations and methodology are derived from [44] and will lead eventually to a simplified equation for recycling effectiveness. For the simple product life-cycle illustrated in Figure 6.4, the aggregated environmental impact at each stage can be expressed as EI. This is the sum of the normalized impact levels, I for all associated impact types.

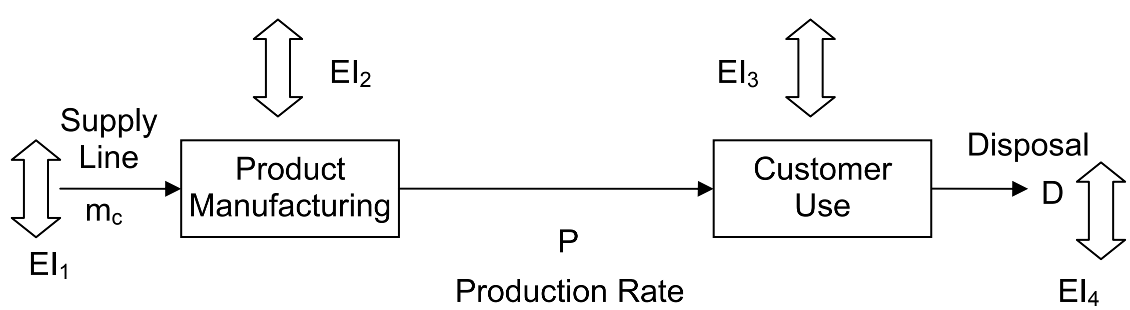

Figure 6.4: Product Life-Cycle [44].

The total life-cycle environmental impact is then:

$$EI_T = EI_1 + EI_2 + EI_3 + EI_4 \qquad (1)$$

The Resource Productivity, RP for each stage is:

$$RP_1 = P / EI_1 \quad ; \quad RP_2 = P / EI_2 \qquad (2a, b)$$

$$RP_3 = P / EI_3 \quad ; \quad RP_4 = P / EI_4 \qquad (2c, d)$$

where *P* is the production rate (product units/year). The largest *RP* indicates the stage that causes the least environmental impact (higher productivity is better). Environmental implications of the product design are usually affected by product reusability and recyclability. A simple recovery operation consisting solely of material recycling is shown in Figure 6.5.

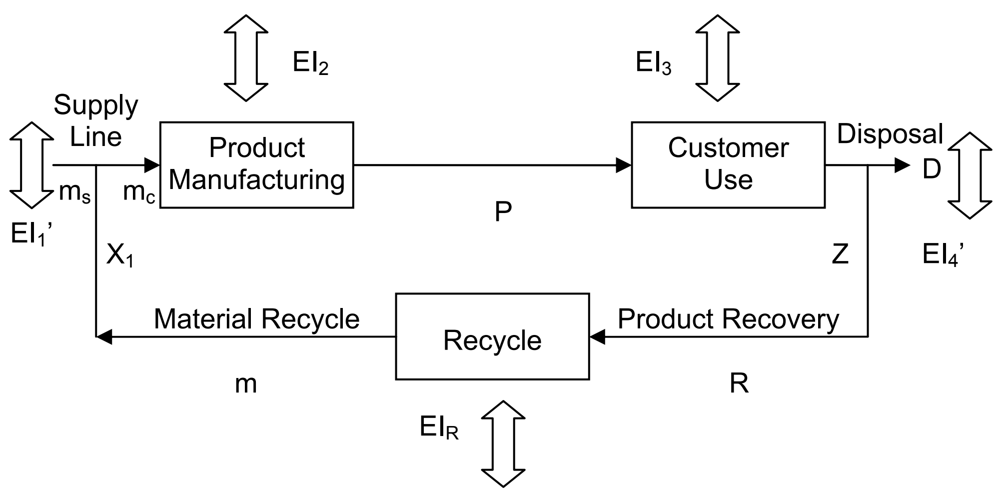

Figure 6.5: Material Cycle [44].

The corresponding *RP* is:

$$RP_R = R / EI_R \qquad (3)$$

This is defined in terms of recovery rate R (product units/year) rather than P, since the purpose of the operation is to manage recovered product. The impact EI_R includes product collection, transport and processing. Recycling will reduce the rate of which materials are obtained from the supply line, m_s (kg/year), and product disposal rate, D. The ratios are:

$$X_1 = m / m_c \quad ; \quad Z = R / P \qquad \text{(4a, b)}$$

Assuming no loss of material during manufacturing and customer use ($m_c = P$), then the efficiency of recycling is:

$$\varepsilon = m / R = X_1 / Z \qquad \text{(5)}$$

In Figure 6.5, those quantities affected by recycling are indicated with (‘).

The modified environmental impacts are then:

$$EI_1' = EI_1(1 - X_1) \quad ; \quad EI_4' = EI_4(1 - Z) \qquad \text{(6a, b)}$$

It is assumed that the recycled component and material mix, m is assumed to be the same as m_c for simplicity, so EI_1 is reduced in direct proportion to X_1. Then the total life-cycle impact is:

$$EI_T' = EI_1' + EI_2 + EI_3 + EI_4' + EI_R \qquad \text{(7)}$$

Recycling is assumed to be beneficial, thus,

$$EI_T' < EI_T \qquad \text{(8)}$$

Substituting Eqn. 1, 6 and 7 into 8, we get,

$$EI_R < X_1 EI_1 + Z EI_4 \qquad \text{(9)}$$

Equation 9 shows that the environmental impact of recycling is less than those from the supply line and final disposal. If EI is substituted in terms of RP from

Eqn. 2 and 3 and using Eqn. 4 and 5 into 9, we will get the minimum acceptable recycling performance, RP_R:

$$RP_R / RP_4 > 1/(1 + \varepsilon RP_4 / RP_1) \qquad (10)$$

When the unialloy aluminum beverage can is put into production and recycled, based on Eqn. 10, we can qualitatively compare the recycling efficiencies of both cans.

6.2 Aluminum Beverage Can Recycling Process Interactive Program

Based on all the implied data from [22-23] and flowcharts from Figure 6.2 and 6.3, an interactive program is created using Microsoft Visual Basic 6.0. This is a flexible program that allows the user to input any arbitrary values. The interface is shown in Figure 6.6. For example, it can be 400 lbs of used aluminum beverage cans or $400 million worth to be recycled. The program will then calculate the melt loss, metal from the potroom needed to replenish the lost metal and also scraps from the process. The result output unit is dependant upon the input unit, for example in Figure 6.2, if the user designated the input as 400 lbs of used aluminum beverage cans, then the result will be in lbs. The results from the program shows the comparison between the recycling of the current dual alloy can and unialloy can. For any program, the result is as good as the governing variables.

We have four governing variables that are preset and loaded into the program each time it is executed or reset. The values for each of these governing variables are; lid to body ratio, skim formation, skim recovery and scrap generation. These are preset from data gathered and compiled in [22-23]. The flexibility aspect of this program lies in the fact that the user would have the ability to change any of these governing variables. For example, if the skim recovery process have been improved because of new technology or because of lightweighting of the can the lid to body ratio is different, the user have the option to change those governing variables. This means that the program has a flexibility built into it to keep up with technology change in the recycling process. The programming is shown in the Appendix A.

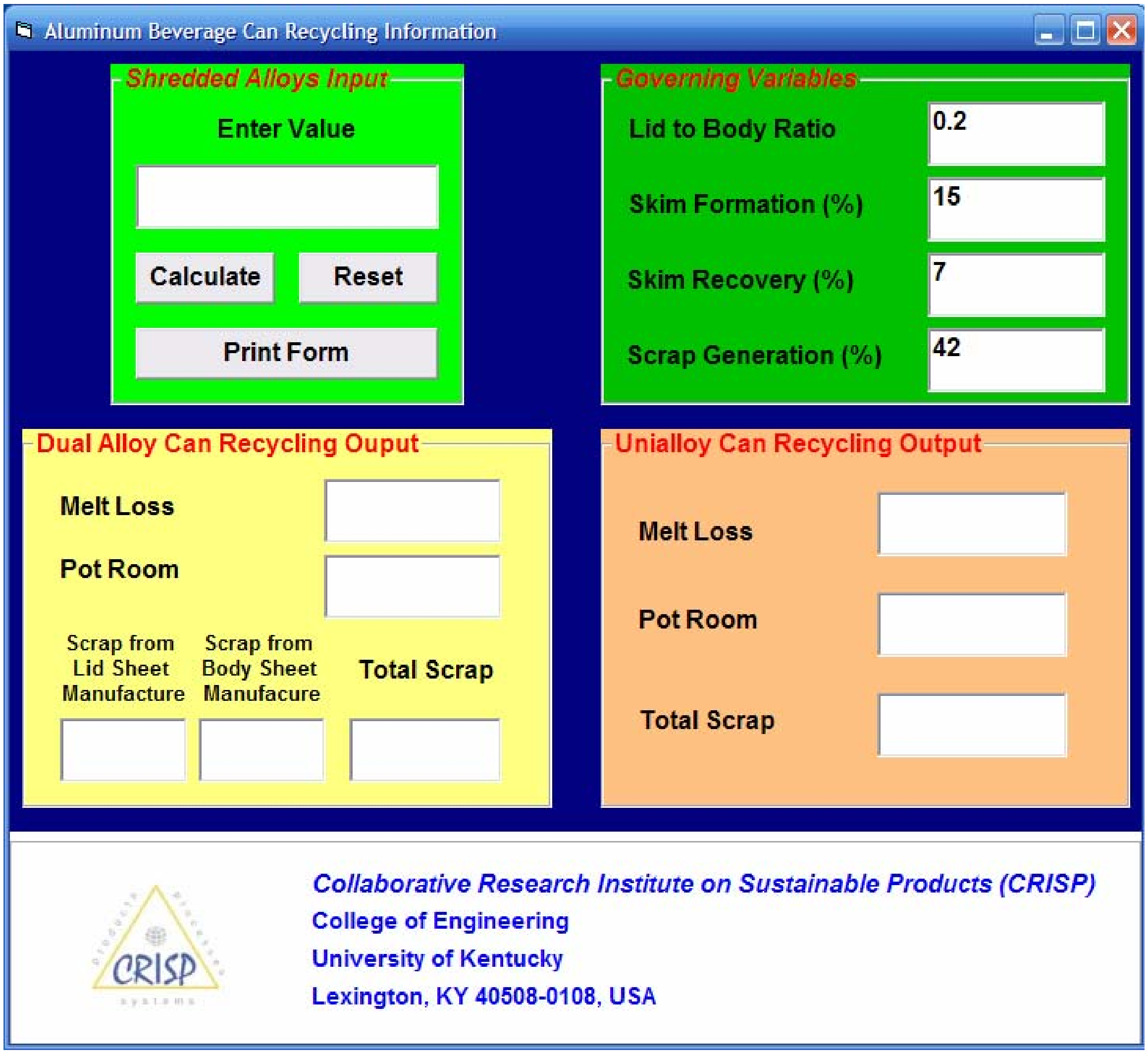

Figure 6.6: Program Interface.

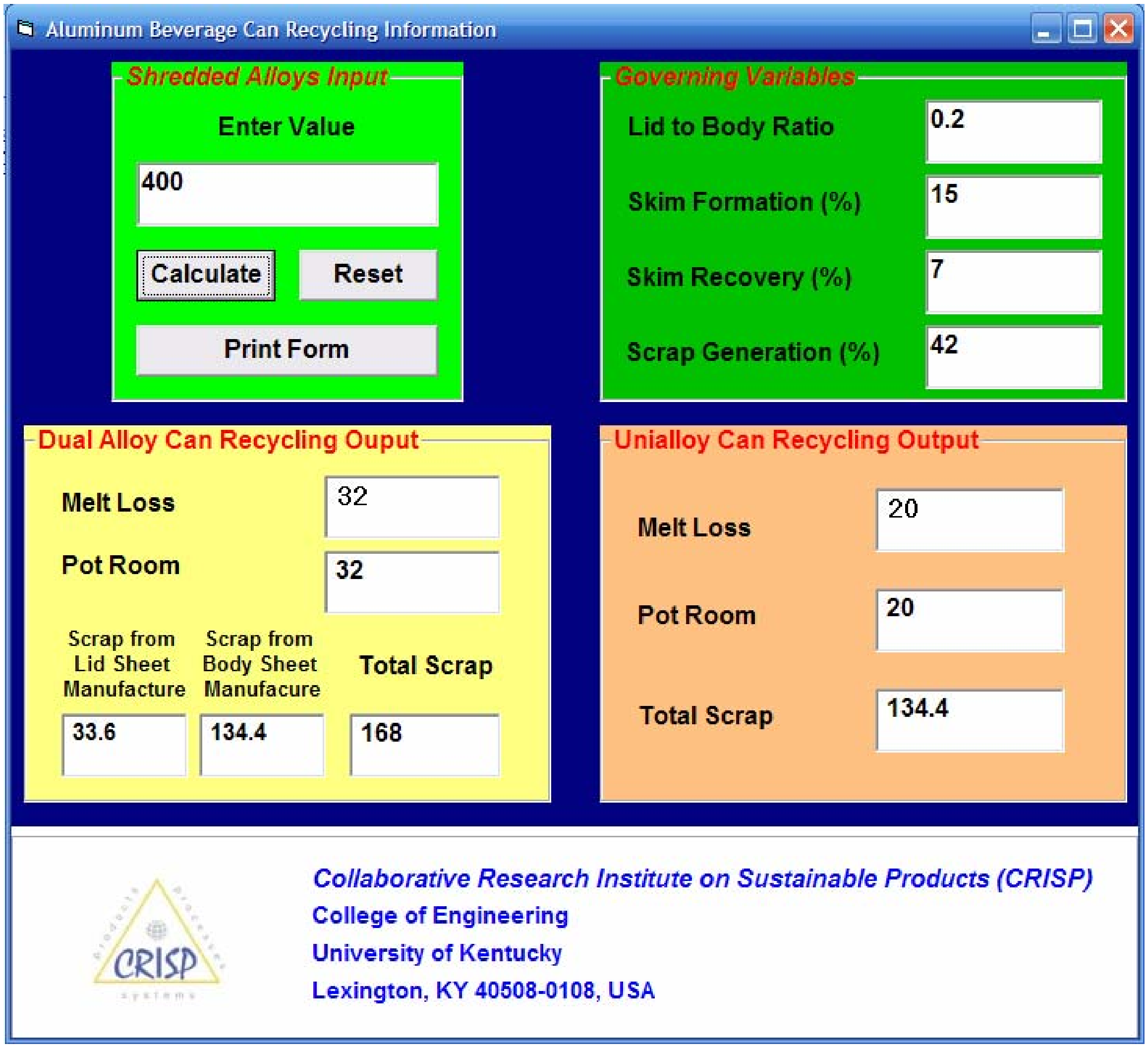

Figure 6.7: Sample Calculations.

Chapter Seven

Discussion and Conclusion

Most sustainable product design methodologies overly emphasize environmental impacts. This is not desirable as in today's business-oriented world, a sustainable product should be economically viable without adverse effect to the environment and society. In addition, life-cycle assessment of sustainable product is done by considering a product as having only one life-cycle, usually from manufacturing and ends with recycling. However, for a truly sustainable product, this is not adequate. A sustainable product should be considered as having multiple and perpetual life-cycles. Its material flow should form a close loop and defined by the 6R concept. The 6R concept is a good tool in Design for Sustainability (DFS) as it maximizes the life of a product and builds improvements into the product after every life-cycle.

The 6R concept was applied to the aluminum beverage can in this case. The sustainable growth and development of the whole aluminum industry is thoroughly discussed and we found that the aluminum beverage can's recycling rate in the United States has been on the decline for the past few years. Since we have also identified recycling as the aluminum beverage can's strongest point, it therefore makes good sense to enhance the recyclability of the aluminum beverage cans in order to increase the sustainability. Recyclability of the aluminum beverage can is tied to all three major elements in sustainability; economy, environment and society. Although we started analyzing and identifying the problem from the system's perspectives, we ultimately solved the problem at the product level. By enhancing the recyclability of the aluminum beverage can from the product design point of view, we are working within the constraints of the current manufacturing, distribution and recycling infrastructure, thus ensuring the new redesigned product would fit perfectly into the current infrastructure. This also means that no huge economic investments are needed to invest in the production of this new aluminum beverage can.

The new aluminum beverage can is designed out of a single alloy; thereby the name unialloy can, as opposed to the current dual alloy construction. The unialloy can eliminates the need for separation of alloy for melting, thus minimizing energy, time and labor use in the recycling process. This ultimately translates into monetary savings. The unialloy can was designed using Pro/Engineer and Pro/Mechanica and structural analysis was done using ANSYS 7.0. Results shows similar performance to the current dual alloy can. An equation for quantifying the recycling performance was adapted from published work and can be used to compare the recycling performance of the unialloy and dual alloy aluminum beverage cans. In addition, an interactive aluminum beverage can recycling program was created based on aluminum can recycling data from published work.

This research starts with the need to enhance the sustainability of the aluminum beverage can. The problem was analyzed from the systems perspectives and solved at the product's design level. A rethinking of sustainable product life-cycle was carried out and the result is the 6R concept. This concept was applied to the new unialloy aluminum beverage can design. The design and analysis of the cans were done using the latest CAD and FEM tools. The cans were shown to be structurally equivalent or even somewhat better. This work serves as an example of taking a product which has been around for a long time with diminishing sustainability, and applying a fresh approach to the problem from a product's perspectives which ultimately leads to improvements at the systems level.

Appendix A: Visual Basic Programming for Aluminum Beverage Can Recycling Process Interactive Program

```
Private Sub Calculate_Click()
SA = Val(SA.Text)
BLR = Val(BLR.Text)
SF = Val(SF.Text)
SR = Val(SR.Text)
SG = Val(SG.Text)
DML = SA * ((SF - SR) * 0.01)
DPR = DML
DSL = (SG * 0.01) * BLR * SA
DSB = SA * ((SG * 0.01) * (1 - BLR))
TS = ((SG * 0.01) * BLR * SA) + (SA * ((SG * 0.01) * (1 - BLR)))
UML = SA * (((SF * 0.01) * (1 - BLR)) - (SR * 0.01))
UPR = UML
US = SA * ((SG * 0.01) * (1 - BLR))
DML.Text = Str$(DML)
DPR.Text = Str$(DPR)
DSL.Text = Str$(DSL)
DSB.Text = Str$(DSB)
TS.Text = Str$(TS)
UML.Text = Str$(UML)
UPR.Text = Str$(UPR)
US.Text = Str$(US)
End Sub

Private Sub Print_Click()
PrintForm
End Sub
```

```
Private Sub Reset_Click()
Dim c As Control
For Each c In Controls
  If TypeOf c Is TextBox Then
    c.Text = ""
  End If
Next
BLR = 0.2
SF = 15
SR = 7
SG = 42
BLR.Text = Str$(BLR)
SF.Text = Str$(SF)
SR.Text = Str$(SR)
SG.Text = Str$(SG)

End Sub
```

References

1. Wanigarathne, P.C., Liew, J., Wang, X., Dillon, O.W., Jawahir, I.S., Assessment of Process Sustainability for Product Manufacture in Machining Operations, Proc. Global Conference on Sustainable Product Development and Life Cycle Engineering, Berlin, September 2004, pp. 305-312.
2. "Our Common Future: From One Earth to One World", 1987, Commission on Environment and Development, Brundtland Commission Report, Oxford University Press, pp. 22-23 IV.
3. Grieβhammer, R., Bunke, D., Gensch, C.O., Produktlinienanalyse Waschen und Waschmittel. Umweltbundesamt, 1997, Ch. 1, p. 10.
4. de Barros Pereira, H.B., de Almeida Souza, P.F., "Design for Sustainability: Methods in Search for a Better Harmony Between Industry and Nature", 5th European Academy of Design Conference, Barcelona, April 2003.
5. Datschefski, E., "Using Nature's Cyclic/Solar/Safe Protocol for Design, Manufacturing and Procurement", Sustainable Products, June 1999, pp. 1-93.
6. Sustainable Products Corporation, www.sustainableproducts.com.
7. Jawahir, I.S., "Sustainable Products: An Introduction to Product Sustainability Rating", Product Sustainability Seminar Series: Seminar 1, University of Kentucky, July 20 2004.
8. Datschefski, E., "Cyclic, solar, safe-BioDesign's Solution Requirements for Sustainability", The Journal of Sustainable Product Design, January 1999, pp. 42- 51.

9. Tipnis, V.A., “Evolving Issues in Product Life Cycle Design”, Annals of the CIRP Annals, Vol. 42/1, 1993, pp.169-171.

10. Walker, S., “Experiments in Sustainable Product Design”, Journal of Sustainable Product Design, October 1998, pp. 41-50.

11. Kaebernick, H., Kara, S., Sun, M., “Sustainable Product Development and Manufacturing by Considering Environmental Requirements”, Robotics and Computer Integrated Manufacturing, Vol. 19, 2003, pp. 461-468.

12. Fuller, D.A., Ottman, J.A., “Moderating Unintended Pollution: The Role of Sustainable Product Design”, Journal of Business Research, 2002, pp. 1-8.

13. “Aluminum in Packaging: Maximum, minimum use of material”, Aluminum for Future Generations, Gesamtverband der Aluminiumindustrie e.V., Düsseldorf, February 2002.

14. Hosford W.F., Duncan John L., “The Aluminum Beverage Can”, *Scientific American*, September 1994, pp. 48-53.

15. Aluminum Beverage Can History, Gesamtverband der Aluminiumindustrie e.V., Düsseldorf, July 2002.

16. “Cans – A Visual History”, www.cancentral.com/brochure.

17. “Crown Expands Shaped-Can Manufacturing. CSD Companies said ‘Taking another Look’ ”, *Beverage Digest*, January 2001, www.beverage-digest.com/ editorial/010126.php.

18. Pinkham M., “Aluminum Cans-History, Development and Market”, *Aluminum International Today*, April/May 2002, http://www.azom.com/details.asp?ArticleID=1483.

19. Reid J.D., Bielenberg R.W., Coon B.A., "Indenting, buckling and piercing of Aluminum Beverage Cans", *Finite Elements in Analysis and Design* 37, 2001, pp. 131-144.

20. Johnson D., "Necking two-piece Beverage Cans in the 90's", Aluminum Alloys for Packaging 2, 1996, pp. 161-177.

21. van Linden J.H.L., "A Mathematical Model of the Aluminum Beverage Can Recycling System", Light Metals, Proceedings of Sessions, AIME Annual Meeting, 1980, pp. 813-825.

22. van Linden J.H.L., "Aluminum Recycling - Everybody's Business, Technological Challenges and Opportunities", Light Metals 1990, pp. 675-682.

23. van Linden J.H.L., "Holistic Aluminum Recycling – Why and How?, 5th Australasian Asian Pacific Conference on Aluminum Cast House Technology, 1997, pp. 111-125.

24 "Aluminium-A Sustainable Material", Gesamtverband Der Aluminiunmindustrie e.V, Düsseldorf, Second Edition 2002, pp 1-22.

25. Jawahir, I.S., Wanigarathne, P.C., "New Challenges in Developing Science-based Sustainability Principles for Next Generation Product Design and Manufacture", International Research/ Expert Conference "Trends in the Development of Machining and Associated Technology" TMT 2004, Neum, Bosnia and Herzegovina, September 2004, pp. 1-10.

26. "Aluminum Industry Vision, Sustainable Solutions for a Dynamic World", November 2001, pp. 1-34.

27. “Industry as a Partner for Sustainable Development: Aluminium”, International Aluminium Institute and United Nations Environment Programme, 2002, pp. 1-37.

28. “Bauxite Mining and Rehabilitation”, Gesamtverband Der Aluminiunmindustrie e.V, Düsseldorf, 2003, pp. 2.1-2.3.

29. “Aluminium-Social Aspects, Aluminum for Future Generations”, Gesamtverband Der Aluminiunmindustrie e.V, Düsseldorf, 2002, pp. 1-18.

30. “Aluminium-Social Aspects”, Gesamtverband Der Aluminiunmindustrie e.V, Düsseldorf, 2003, pp. 12.1-12.2.

31. “Aluminium is Used and Not Consumed”, Gesamtverband Der Aluminiunmindustrie e.V, Düsseldorf, 2003, pp 7.1.

32. Testin, R. F., “Aluminum Recycling-Potential and Problems”, Journal of Metals, September 1981, pp. 21-24.

33. Bruggink, P.R., Martchek, K.J., “Worldwide Recycled Aluminum Supply and Environment Impact Model”, TMS Light Metals 2004, pp. 907-911.

34. Jawahir. I.S., Dillon Jr., O.W., Rouch, K.E., “Product and Process Sustainability: New Challenges for Design and Manufacture”, Seminar Presentations at GM R & D Center, Warren, MI, August 16, 2004.

35. Liew, J., Rouch, K., Das, S., Jawahir, I.S., “A Methodology for Evaluating Sustainable Aluminum Beverage Can Designs”, Aluminum Alloy for Packaging, 2005 TMS Annual Meeting Presentation, San Francisco CA, February 14, 2005.

36. “Aluminum Facts at a Glance”, The Aluminum Association Inc., September 2003.

37. Aluminum Beverage Can - Facts and Figures, Gesamtverband Der Aluminiunmindustrie e.V, Düsseldorf, 2003, pp. 15.1-15.2.

38. Das, S.K., Long III, W.J., Hayden, H.W., Green, A.S., Hunt Jr., W.H., “Energy Implications of the Changing World Supply of Aluminum Metal Supply”, Journal of Metals, August 2004, pp. 14-17.

39. “The Next Big Thing”, Aluminum Now, Vol. 6, No. 6, November/December 2004, http://www.aluminum.org/ANTemplate.cfm?IssueDate=11/01/2004.

40. Graedel, T.E., “Chapter 2: The Concept of Life-Cycle Assessment”, Streamlined Life-Cycle Assessment, 1998, pp. 18.

41. Sutherland, J., Gunther K., Allen, D., Bauer, D., Bras, B., Gutowski, T., Murphy, C., Piwonka, T., Sheng, P., Thurston, D., Wolff, E., “A Global Perspective on the Environment Challenges Facing the Automotive Industry: State-of-the-Art and Directions for the Future”, International Journal of Vehicle Design, Vol. 35, Nos. 1/2, 2004, pp. 86-110.

42. “Avoid being forced to discuss “environmental impact”- consider sustainability and not “pure ecology”” Gesamtverband Der Aluminiunmindustrie e.V, Düsseldorf, 2003..

43. Romanko, A., Berry, D., Fox, D., “Simulation of Double-Seaming in a Two-piece Aluminum Can”, Materials Processing and Design: Modeling, Simulation and Applications, NUMIFORM 2004, pp. 1526-1532.

44. Dickinson, D.A., Caudill, R.J., “Sustainable Product and Material End-of-Life Management: An Approach for Evaluating Alternatives”, IEEE International Symposium of Electronics and the Environment 2003, pp. 153-158.

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