END-OF-LIFE ANALYSIS OF ADVANCED MATERIALS

A Dissertation by

Eylem Asmatulu

Master of Science, Cukurova University, 2004

Bachelor of Science, Cukurova University, 2001

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The following faculty members have examined the final copy of this dissertation for form and content, and recommend that it be accepted in partial fulfillment of the requirement for the degree of Doctor of Philosophy, with a major in Industrial Engineering.

Janet Twomey, Committee Chair

Michael Overcash, Committee Member

Vinod Namboodiri, Committee Member

John Perry, Committee Member

Esra Buyuktahtakin, Committee Member

Accepted for the College of Engineering

Vishwanath Prasad, Interim Dean

Accepted for the Graduate School

Abu Masud, Interim Dean

DEDICATION

To my family and friends
for their unconditional love and support.

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CHAPTER 1

END-OF-LIFE ANALYSIS OF ADVANCED MATERIALS

1.1 INTRODUCTION

1.2 General Background

Advanced materials refer to all the new and modified materials that represent advances over the traditional materials (Rensselaer,2004). These materials usually perform much better than traditional materials when in service because of their superior properties (e.g., high strength, high corrosion resistance, low density, etc.). Additionally, these materials can be tailored to sustain specific applications at different conditions, and used in various new technologies, such as pocket-sized computers, jet engines and computer chips (Arabe, 2003). Life cycle assessment (LCA) is a broad analysis tool to evaluate these materials from the production stage to the end-of-life (EOL), and their influences on the environment, economy, and human health. The definition of the EOL for a product is a specific point at which the product does not satisfy the initial purchaser or owner needs. Even though the research and development of advanced materials have been growing significantly for a couple of decades, life cycle analysis of these materials has not been widely studied and documented yet.

This dissertation has four major objectives, each of which was published as a separate journal paper. The first three objectives are focused on the EOL of the advanced materials, while the fourth objective concerns the economic and environmental impacts of recycling aircraft materials. The objectives and motivations of this dissertation are given below:

- **Life Cycle and Nano-products: End-of-life Assessment**

Understanding the economic and environmental impacts of advanced materials in many fields necessitates analyzing the life cycle profiles for future considerations. The emphasis of the materials' EOL cycle studies is mostly on the environmental and health effects of the products during the production, usage and recycling/reusing stages. This study highlighted the results of the preliminary assessments of the EOL stages of the advanced materials and devices, which can possibly be used as efficient and low cost materials in different industries.

- **Recycling of Fiber Reinforced Composites and Reusing in Different Fields as Low Cost Products**

A number of advanced materials and components are used in the production of aircraft at various stages. The local Wichita aircraft companies recycle these materials after or during the production stages. The main idea of this study is to explore the contribution of aircraft recycling to sustainable manufacturing, as well as the environmental and health benefits in the region.

- **Recycling of Aircraft – State-of-the-Art**

  The purpose of this study is to investigate the environmental benefits of aircraft recycling and reuse of recycled materials in the same or similar applications as low energy input materials.

- **Evaluation of Recycling Efforts of Aircraft Companies in Wichita**

  This study confirms that many high-tech products (e.g., nanoproducts, composites and aircraft parts) appear to have high recycling potential which leads to the use of fewer natural resources, and also consumes less energy to recreate several advanced products/parts for the sustainability of the manufacturing processes. Because of the environmental and economic considerations of nanomaterials, composites and aircraft parts, it is desirable to increase the recycling rates of these materials and parts for use in other products.

1.3 Major Contributions of This Study

The present study makes significant contributions in terms of energy, environment, economics and sustainable developments. Some of the major contributions are briefly summarized below:

- **Sustaining the material flow to manufacturing:** Secondary resources (solids and liquids) are obtained from the recycling process of materials, and parts are studied, tabulated, and analyzed. Recycling and reusing processes provide significant contributions to sustainable resources management because of the valuable secondary raw materials flow into the production systems. As a result, this process cycle will save primary resources for a longer materials life cycle.

- **Increasing the social awareness:** Scientific communities and other readers will gain some information about advanced materials and their EOL consequences. The information provided in this dissertation will potentially reduce public concerns regarding the recycling and reusing issues.
- **Reducing greenhouse gas emissions that contribute to global climate change:** The climate changes have already started showing their unpleasant faces by having longer drought seasons; heavy rains, hails and snows; wind and dust storms; and tornadoes, hurricanes and floods. We should be respectful of our fragile ecosystem by reducing greenhouse gases with the recycling and reusing processes greatly.
- **Reducing the amount of waste sent to landfills and incinerators:** Landfilling can be another big concern because of leaching of toxic materials to underground water sources, destroying the valuable resources. Also, burning the recyclable waste in incinerators will not only produce toxic gases and ashes, but also reduce the energy values of those recyclable materials and products.
- **Preventing pollution by reducing new raw materials**: Recycling and reusing will greatly limit solid, liquid and gas emissions and reduce the demands on the new raw materials.

1.4 Main Organization of PhD Dissertation

This PhD dissertation is organized by topic corresponding to published journal papers. There are four topic areas corresponding to chapters 2 through 5. The sections below briefly describe each topic published as a separate journal paper.

1.5 Paper 1: Life Cycle and Nano-products: End-of-life Assessment

Investigating the EOL stage of nanomaterials is of great interest for the environmental impacts or economic benefits of these materials during production and consumer use. In a recent study, the authors used the Woodrow Wilson Center's Project on Emerging Nanotechnologies (PEN) Consumer Products Inventory (CPI) model, which contains the largest nanoproduct list (1,014 commercially available nanomaterials) as of 2010 (PEN, 2010). The consumer products show a wide collection of nanomaterial applications, such as clothing, personal care products, medicine, electronic, defense, transportation, sensors, sporting goods, etc. Due to the detailed EOL cycle of the nanoscale materials and devices, the authors divided these 1,014 nanoproducts into the nine EOL categories (e.g., recyclability, ingestion, absorption by skin/public sewer, public sewer, burning/landfill, landfill, air release, air release/public sewer, and others) that rely on the possible final destinations of the nanoproducts (PEN, 2010). This study explores the initial evaluation of the EOL stage of several nanoproducts to define the end of life fate of nanoproducts, and then minimize the effect of nanoproducts on the environment.

The PEN CPI of the nanoproducts is analyzed in detail, and the EOL categories are presented to determine the largest EOL recyclability potential of these materials (40%) (Figure 1.1). At lower frequency, human uptake is about 25%, while landfills is about 20%. Release to water (8%) and air (6%) are much lower for the current nanoproducts.

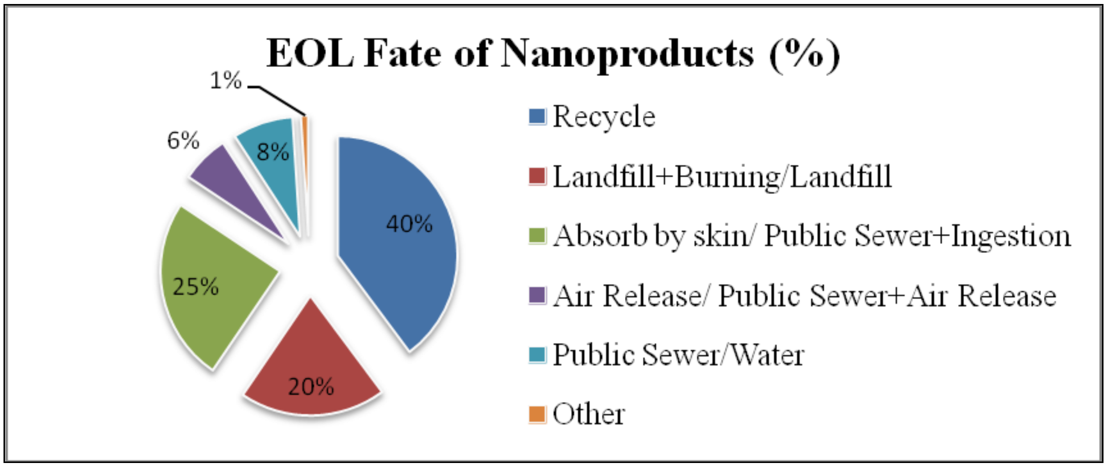

Figure 1.1 End of life fate of nanoproducts.

The authors determined that a large quantity of nanoproducts used for various materials and device fabrications could be recycled and reused for different applications. Some of the nanoproducts could be absorbed by the skin or up taken by the body through ingestion and inhalation, while the remaining ones could be delivered to the landfills, air and sewer systems. Since a few nanomaterials are toxic, these latter nanomaterials need to be particularly recycled and reused without contaminating the air, soil, water, as well as livestock and vegetation, through which humans can be poisoned in the long term.

This work has been published in the *Journal of Nanoparticles Research*:

- Asmatulu, E., Twomey, J., and Overcash, M., 2012. "Life Cycle and Nano-products: End-of-life Assessment" *Journal of Nanoparticles Research* (2012) 14:720 DOI 10.1007/s11051-012-0720-0.
- Asmatulu, E., Twomey, J., and Overcash, M., 2011. "End-of-life Investigation of Nano-Products" Kansas NSF EPSCoR Poster Presentation, January 12-13, 2011.

1.6 Paper 2: Recycling of Fiber-Reinforced Composites and Direct Structural Composite Recycling Concept

A composite is a complex structured material made of two or more distinct materials, particularly ceramics, glasses, carbons, metals and/or resins, merged to produce structural or functional properties that do not exist in other forms of materials. Considering the composite applications, thermoset resins are the most frequently used matrix materials. Fiber reinforced polymer composites are preferred for various structural applications due to their high strength-to-weight and stiffness-to-weight ratios. While the service life of these materials in diverse applications is approximately 15 to 20 years, recycling is the most logical way to dispose of composite materials since these advanced materials usually maintain these physical properties after the service life (ACP

Composite, 2011). Major recycling methodologies for glass and carbon fiber reinforced composites include chemical, mechanical and thermal recycling techniques. The aim of this study is to compare the recycling methodologies of the fiber reinforced composites and the authors' approach, the direct usage of composite materials, after small modifications, as raw materials for the same or different industries (Composite Products, Inc.2011. & Molnar, A., 1995).

The new methodology is called "direct structural composite recycling". The main principle of the concept is that large composite parts can be cut into small size structural pieces to be directly used in various fields. Then, the new composites can be used as a low cost product since most composites keep their physical and chemical properties after certain use (20-25 years).

Reusing composites with the direct structural method is highly promising, so this method can be more economical and environmentally friendly than current alternatives, where the fiber lengths and their futures are reduced. Potential markets are also investigated based on the economic returns of the direct recycled composites.

This work has been published in the *Journal of Composite Materials*:

- Asmatulu, E., Twomey, J., and Overcash, M., 2013. "Recycling of Fiber-Reinforced Composites and Direct Structural Composite Recycling Concept." *Journal of Composite Materials* February 20, 2013 0021998313476325

1.7 Paper 3: Recycling of Aircraft: State of the Art in 2011

Presently, the end-of-service life of many aircraft has become the key subject for the recycling of aircraft and their parts in the globe. It is estimated that in the next 20 years approximately 12,000 aircraft currently in use will be at their end of service. Hence, reclaiming retired aircraft in an environmentally safe manner while retaining some value becomes a significant need for the aircraft recycling industries. The study evaluates the aircraft recycling opportunities and the reuse of their parts as raw materials in other productions. This will considerably reduce the environmental concerns of the aging aircraft and sustainable aircraft manufacturing. In this study, the authors investigated the environmental benefits of aircraft recycling and reuse in the same or similar applications as low energy input materials. We believe that recycled aircraft materials and devices will make a significant impact on the environment and health, and also create sustainability and new job opportunities in the region.

Recycling provides a number of different benefits to the environment and economy. The major components that can be recycled from aircraft include carbon and glass fiber composites, wires, electronics, aluminum and other alloys, stainless steels, and many other organic and inorganic compounds. By reducing the amount of energy used by the industry, recycling reduces greenhouse-gas emissions and minimizes global climate change. Additional benefits of recycling would be a reduction in emissions from incinerators and landfills (Carberry, W., 2008. & Composite Products, Inc., 2011).

Recycling aircraft parts and reusing them in different purposes will further reduce the use of natural resources, energy costs, mining operations and landfill allocations. In addition to these benefits, recycling aircraft will reduce gas, solid and liquid emissions, and energy demand compared to the virgin material production, which can require higher energy consumption, create emissions and cause other concerns.

This work has been published in the *Journal of Industrial Engineering*:

- Asmatulu, E., Overcash, M., and Twomey, J., 2013. "Recycling of Aircraft: State of the Art in 2011" *Journal of Industrial Engineering.* Volume 2013, Article ID 960581, 8 pages. http://dx.doi.org/10.1155/2013/960581

1.8 Paper 4: Evaluation of Recycling Efforts of Aircraft Companies

Due to the high demand of airline transportation, the number of manufactured aircraft has been increasing worldwide. There are many advanced materials used for aircraft manufacturing, including composites, metals and alloys, wires, wood, paper, plastics, electronics, and avionics. After aircraft production, some advanced materials or parts remain in the leftover or scrap forms. Many aircraft companies have been recycling these materials to remanufacture aircraft parts or other products for more sustainable production in environmental and economic concerns.

The purpose of this study is to analyze the recycling efforts of aircraft companies in Wichita, Kansas. Life-cycle assessment was used to analyze the recycling efforts of the aircraft companies that mainly focus on cradle-to-gate energy, greenhouse gas emissions

(CO_2), virgin material replacement with recycled materials, and natural resources usage. The energy savings from recycled aircraft materials is 840.8 million MJ/year. This savings can annually power 10,510 households' worth of electricity consumption in Wichita, KS. The reduction in CO_2 emissions associated with the aircraft material recycling (61.1 million Kg) is equivalent to the yearly tailpipe CO_2 generation of 11,980 average vehicles with 12,000 miles of an annual use. The results also show that recycling aircraft materials and parts contributes to sustainable manufacturing, as well as environmental and health benefits in the Midwest.

The result of this study indicated that recycling aircraft materials offers considerable economic and environmental benefits. Considering production from the recycled materials require less energy, and also generates much lesser CO_2 emissions compared to the production of virgin materials. These benefits also lead to a sustainable manufacturing of aircraft in the town.

- This work has been submitted to the Journal of Resources, Conservation and Recycling.

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CHAPTER 2

LIFE CYCLE AND NANO-PRODUCTS: END-OF-LIFE ASSESSMENT

2.1 ABSTRACT

Understanding environmental impacts of nanomaterials necessitates analyzing the life cycle profile. The initial emphasis of nanomaterial life cycle studies has been on the environmental and health effects of nanoproducts during the production and usage stages. Analyzing the end-of-life (EOL) stage of nanomaterials is also critical because significant impacts or benefits for the environment may arise at that particular stage. In this article, the Woodrow Wilson Center's Project on Emerging Nanotechnologies (PEN) Consumer Products Inventory (CPI) model was used, which contains a relatively large and complete nanoproduct list (1,014) as of 2010. The consumer products have wide range of applications, such as clothing, sports goods, personal care products, medicine, as well as contributing to faster cars and planes, more powerful computers and satellites, better micro and nanochips, and long-lasting batteries. In order to understand the EOL cycle concept, we allocated 1,014 nanoproducts into the nine EOL categories (e.g., recyclability, ingestion, absorption by skin/public sewer, public sewer, burning/landfill, landfill, air release, air release/public sewer, and other) based on probable final destinations of the nanoproducts. This article highlights the results of this preliminary

assessment of EOL stage of nanoproducts. The largest potential EOL fate was found to be recyclability, however little literature appears to have evolved around nanoproduct recycling. At lower frequency is dermal and ingestion human uptake and then landfill. Release to water and air are much lower potential EOL fates for current nanoproducts. In addition, an analysis of nano-product categories with the largest number of products listed indicated that clothes, followed by dermal-related products and then sports equipment were the most represented in the PEN CPI, 2010.

2.2 INTRODUCTION

The definition of EOL for a product is a specific point at which the product does not satisfy the initial purchaser or owner needs. At the EOL, a product has a fate or destination which can range from disposal in the environment to reuse. This applies to all products, including nanotechnology products (nanoproducts or nanomaterials). Twenty four countries in the world are estimated to currently use nanotechnology to produce different nano-products (PEN, 2010). According to Senjen, there were 700 nano-products on the market by 2006, but most of these were not labeled or publicly known (Senjen, 2006). The Woodrow Wilson Center's Project on Emerging Nanotechnologies (PEN) catalogued 1,014 nano-products in August 2009 (Consumer Products Inventory, CPI). The PEN CPI is a convenient catalogue attempting to document the magnitude and diversity of products referred to as nano-products, those apparently containing or using nano-materials as a part of the product. The PEN CPI also primarily contains consumer products, but also some industrial products. However, the criteria to be on the PEN CPI list may be imperfect (Berube et. al., 2010), and might better be referred currently as a fuzzy image of the nanoproducts classification. A primary concern with the PEN CPI is that actual presence in the marketplace is not confirmed nor is the list updated frequently (Berube, et. al., 2010). Thus, nanoproducts are one class of products for which better understanding of the EOL phase of the life cycle analysis can be used to improve the environmental impact.

The EOL flow of the large number of products from society provides a framework for the small number of products that are now labeled as nano. The EOL is largely dictated by the infrastructure established by society to manage these products. Where recycling infrastructure has grown, this EOL alternative is generally viable and can be looked upon to expand for similar products or materials. Infrastructures for treating discharges as wastewater are also in place. Additionally infrastructure for landfill and incineration operate to manage large portions of EOL products. The assumption made here is that these infrastructures would be used in an analogous way for respective nanoproducts. The only difference might be that if nanomaterials are very expensive, there would be a greater incentive for recovery. However, this has yet to be identified on a wide-spread basis nor does this preliminary evaluation address enhanced technologies (separation, extraction, purification, etc.) to recover nanomaterials. However, nanoproducts may just be recycled without recognition of the nanocontent.

Analyzing the EOL stage of a product is critical because significant impacts or benefits for the environment may arise at that stage. Discarding used product to the landfill or mixing with wastes in the public sewer may not be the preferable end-of-life fate for the products. Generally, environmental benefits accrue when products are recycled because of the reutilization of materials, thus preventing consumption of limited natural resources. Based on the EOL strategy of a product, product designers can produce recyclable, easy to remanufacture, and simple to disassemble products which will reduce the environmental effect and energy consumption of products. Material selection is also an important step in designing environmentally friendlier products. In addition, product recovery through recycling and remanufacturing minimizes the amount of waste transferred in landfills. Thus the main benefits of analyzing nanoproduct EOL are to produce ecologically acceptable products, expand techniques for product recovery, and enhance waste management skills (Gungor and Gupta, 1998)

There is a relatively small literature on recycling nanoproducts. Recycling of nanoscale materials necessitates collecting used nanomaterials, separating the compounds, and recovering and reusing in the same or different products. Separation and recovery processes can be achieved using various physical, chemical, and physicochemical methods. Combustion is another nanowaste treatment method where nanoscale products, such as carbon in materials, polymers, and similar compounds can be burned to reduce the environmental effects or to produce heat energy (Piotrowska et al. 2009).

Nanoscale metallic and ceramic materials can be melted to produce bulk materials where the bulk materials can be utilized in a different industry for various purposes, and also potential toxicity of nanoscale products can be minimized in this way. Melting temperatures of the nanoscale materials will deviate from the corresponding bulk materials (Olapiriyakul and Caudill 2009). Most of the time, the melting temperatures are considerably reduced at the nanoscale due to the high surface area, energy, and broken atomic bonds on the surfaces, which can significantly lower the emission and cost of recycling and treatment processes. The environmental impact of the nanoproducts discarded to the landfills will thus be drastically reduced.

Lloyd and Lave, 2003, investigated economic and environmental impacts of nanocomposites in the automobile industry, and found that recyclability and reparability are important for this industry. Most of the metal parts (approximately 80%) in the motor vehicle are recycled, while most of the plastics are shredded and dumped to the landfills. Polymeric (nylon) based clay (e.g., montmorillonite and kaolin) nanocomposites gained much attention for the industry and several research programs have been conducted in this field. Some of the clay-based nanocomposites have been used in the automobile industry because of the strength and high flame resistant of the new material. It was stated that these nanocomposites can be recycled without further changes on the materials and used in the same field (Lloyd and Lave, 2003). Fiber reinforced composites have a very long service lifetime as long as the polymeric parts of these composites are protected from the environmental effects (e.g., UV light, moisture, oxygen and ozone, acids, and pigments). Generally, polymeric coatings are used to protect the composite from the environmental effects. However, polymeric coatings experience physical, chemical, and physicochemical deterioration as the result of these aggressive conditions. Recently, the surfaces of composites are coated with carbon nanotubes (CNTs) associated polymeric coatings in order to protect the composites (Asmatulu, et al., 2010). At the end of the composite life cycle, CNTs in the polymeric coating can be removed from the surface of the composites and acid digested to separate the CNTs from the coating in addition to combustion. The process during the acid digestion may reduce the length of CNTs, which is another concern to be considered.

The study described in this paper had several objectives. At the broadest level an objective was to minimize the effect of products on the environment by bringing greater focus to the EOL stage. The second objective was to provide a preliminary assessment of EOL for the specific class of products labeled as nano-products. These have been the focus of attention with regard to manufacturing and consumer effects, but a unified evaluation of nanoproduct EOL can help improve the overall life cycle characteristics of nano-products. The third objective was to develop a preliminary assessment of the potential for nano-product recycle/reuse since nanomaterials have higher material costs and may have high reuse life cycle credits and thus be important to the field of nano-products.

2.3 METHODOLOGY

This study is based on using the comprehensive PEN CPI list of 1,014 nano-products as documented on February 18, 2010 (PEN, 2010). The PEN list is the largest nanoproduct compilation currently available. The PEN CPI categorized nano-products into the eight different application areas, appliances, automotive, cross-cutting, electronics and computer, food and beverage, goods for children, health and fitness, and home and garden. Each category has subcategories, for example, the health and fitness category has clothing, cosmetics, filtration, personal care, sporting goods, and sunscreen. The EOL study did not use this concept of product application categories for analysis, but instead used an EOL framework, described below.

The critical distinction made in this research is that products and specifically nanoproducts have the potential or expected likelihood of a certain EOL category. These potentials are assigned with a general set of assumption related to nano and closely related non-nano products. These categories reflect that after the use phase, a product or components of a product are in three general physical states, a) gas or volatile liquid, b) liquid to be managed as wastewater, and c) a product or solid material. There three states were expanded into nine categories used elsewhere for environmental fate (FRS; Allen and Rosselet, 1997; E-FRAT). These nine categories were used to assign each nanoproduct to an EOL category (as described in the results and discussion section). This is not a declaration that the product is completely in one category or in the case of recycle that it is currently recycled. The preliminary categorization herein gives a broad distribution or framework from which more detailed research on actual products or the overall distribution would be done. The rubric for categorization is given in the results section.

The first step of our methodology was to group similar products into one category. This reduced the 1,014 nano-products to 294 nano-product groups. As an example for shampoo, there are different companies producing shampoos under the different brand names but all of these eventually contain nanomaterials and applications that are very similar, so we group these as one. Also, there are different companies producing the same products, such as clothes and selling under the different names and types. The PEN CPI nano-products list consists of 137 clothing products which include fabric, shirt, pants, dresses, socks etc. Eventually, most of the clothes EOL destinations are the same (recycling); thus, instead of using 137 products we gathered all clothes elements under the one product entry. We can define clothes as a recyclable product due to the equivalency of non-nano-product clothing reuse (such as, donating to people who need clothing). After the reuse, clothes scrap may go to landfills. Furthermore, the PEN CPI counted 35 sun screen body lotions that consumers use only once because no matter what protection factor (SPF) or chemical composition, the common sun screen products EOL are same, which is absorbed by the skin or washed away. Thus, it is not necessary to count each sun screen body lotion individually.

The second step of our methodology was to categorize the EOL of the 294 nano-product groups. As a preliminary framework, each of the 294 product groups was assigned to one EOL category. This binary approach reflects the preliminary stage of any analysis, since no previous attempts have been made to examine EOL for nanoproducts. Future studies might be able to do field surveys to subdivide into multiple EOL categories, but those marketplace assessments for 1,000+ products are not currently available and so a preliminary, simpler categorization binary rule was adopted.

2.4 RESULTS AND DISCUSSION

The complete classification of the 294 nano-product groups was based on the estimated primary EOL. These are shown in the supplementary information for this paper, so that a transparent list is available to the reader. The supplementary information has six information columns, including number of products (1-294), EOL, product names, number of similar products combined, applications, and specific use in the products (usually where the nanoproduct is located). The PEN data do not consistently designate how the nanomaterials are included in each product and so we cannot decide the nanomaterials recycle potential because physical and chemical properties of nanomaterials can be changed, and so nanomaterials recyclability options may be reduced. The product can still be recycled as an actual entity.

Nine categories of EOL groups were first selected;

1) recycle,

2) ingestion,

3) absorbed by skin then public sewer or water body,

4) public sewer or water body,

5) burning then landfill,

6) landfill,

7) air release,

8) air release then public sewer or water body

9) others

The criteria to assign an EOL fate to each nano products are described below. These EOL groups are so widely studied and written about that no references or descriptions of these technologies are needed. We recognize there may be multiple fates for any given nano-product, but have tried to assign each nano-product to just one primary fate category.

Recycling is a process of collecting used materials to produce new products so that potential value of EOL products will not be lost (The League of Women Voters, 1993), and thus recycling is one EOL category which was used. Product recycling depends substantially on an infrastructure for collection, technology for recycle or reuse of a product or material in a product, and the economic value of products. With respect to nano-products, even with an imprecise catalogue (PEN CPI) it should be possible to begin analysis of EOL of these products. Nano-products EOL were assigned to recycling if similar non-nano-products are generally mentioned as recycled. Thus, non-nano batteries are recycled and so the nano product battery EOL was also categorized as recycle. This serves to identify the potential that EOL batteries may offer as the ability to recycle the nano material in such batteries. As another example, non-nano lubricants are often recycled or reused as a fuel in transportation vehicles hence nanoproduct lubricant was assigned to this EOL category. Cost-benefit analysis of whether recycling is viable was not done in this study. Besides the economical analysis, environmental benefits such as reducing resource use, waste minimization, and protecting human health play essential roles for the decision on material recyclability, but were not quantified herein. Resources such as earth911 and Department of Public Works Milwaukee were also used to help indentify product recycling (Earth 911, 2010; Department of Public Works Milwaukee, 2010)

Ingestion is another category in which nano-products were assigned, if taken into the body by drinking or eating. Either these will dissolve and stay in the body or are excreted to the public sewer system. The information to separate retention versus excretion was not available and so all were listed as ingested.

A third category was for nano-products that are **absorbed by the skin** and in part washed away and delivered to **public sewers or body of water**. Some examples can be body lotion or sun screen products, some of which contain nanomaterials.

Direct discharge to the **public sewer** is the fourth category. Laundry detergent is an example nano product that at the end of the cleaning steps, mostly goes to the public sewer.

Burning/landfill was the fifth category as nano products (e.g., engine oil) can be burned in an incinerator and ashes can be sent to the landfill. The burning processes can be beneficial for the hazardous and clinical wastes that cannot be directly sent to the landfill. After the incineration process, the bottom and fly ash of hazard wastes can be typically landfilled. These nano-products tend to be disposable medical-related products.

Landfill is the sixth category and is based on the lack of any apparent alternative in the other EOL categories.

The seventh category is nano-products that can be partially released to the **air**. As an example, odor eliminator spray or other gas or solvent products can be released to air.

The eighth category is a small subset of nano-products that can be lost to the **air** in use but also transferred by rain from the point of use to **public sewer or body of water,** such as surface coatings.

Other is the smallest category and reflects product EOL that are difficult to put the product in one EOL category. For instance, plant grow mixture is given to the plants, which can be mixed with surface water by runoff but that can also be consumed by human and animals. Thus, it is very difficult to define a sequence and EOL.

The condensed grouping of 294 nano-products were thus examined individually and assigned to an EOL category. These are shown in the supplementary information Table 2.1 for this paper, so that a transparent list is available to the reader. While there may be alternative category choices for any one of these nano-products, the general results by category remain primarily the same. Where multiple similar products were grouped together this can be seen in the column entitled number of similar products combined, thus relating the 1,014 PEN CPI list to the recombined list of 294 nano-products.

Figure 2.1 shows a distribution by number of the 1014 products based on the EOL stage. In Figure 2.2 we graphed the same EOL destination utilizing the categorization (294 groups) of this research to reduce duplication. Figure 2.2 verified that the categorization did not distort the EOL distribution, since Figures 2.1 and 2.2 generally agree with the relative EOL categories, except the absorb by skin/public sewer and landfill are reversed. Also it must be noted that these distributions are only of product or product groups and do not reflect the actual magnitude of products in the market place and used by consumers. As is seen from the Figures, a majority of the used products have potential for recycle. The other categories are as shown.

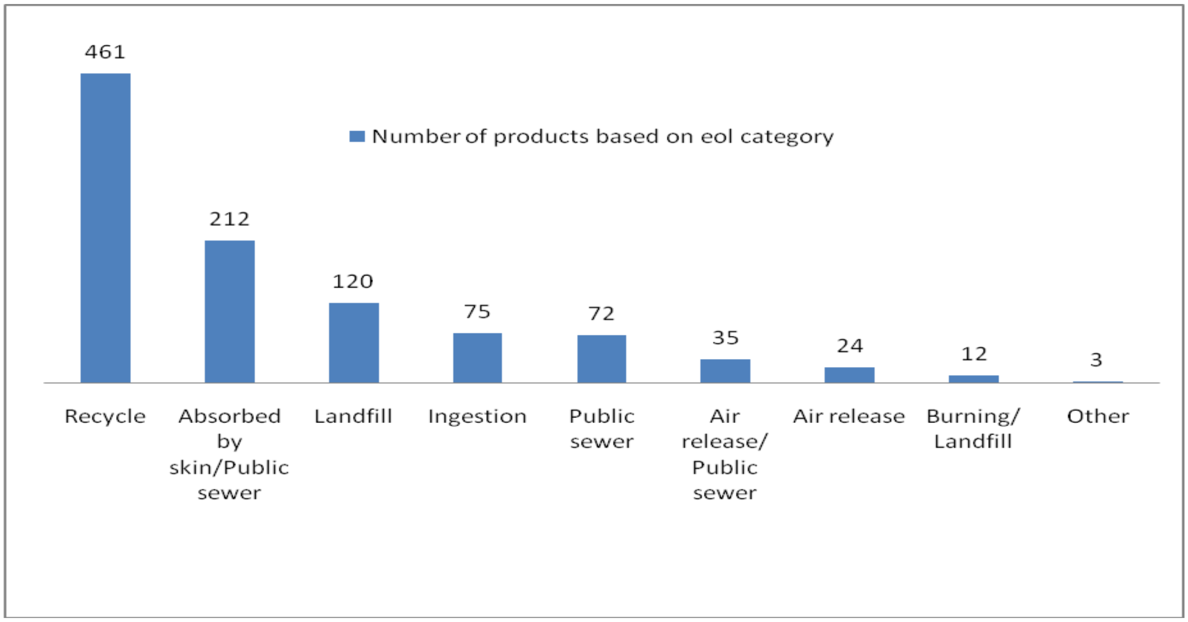

Figure 2.1 Nano-product distribution based on the EOL, total PEN CPI list (1014 products).

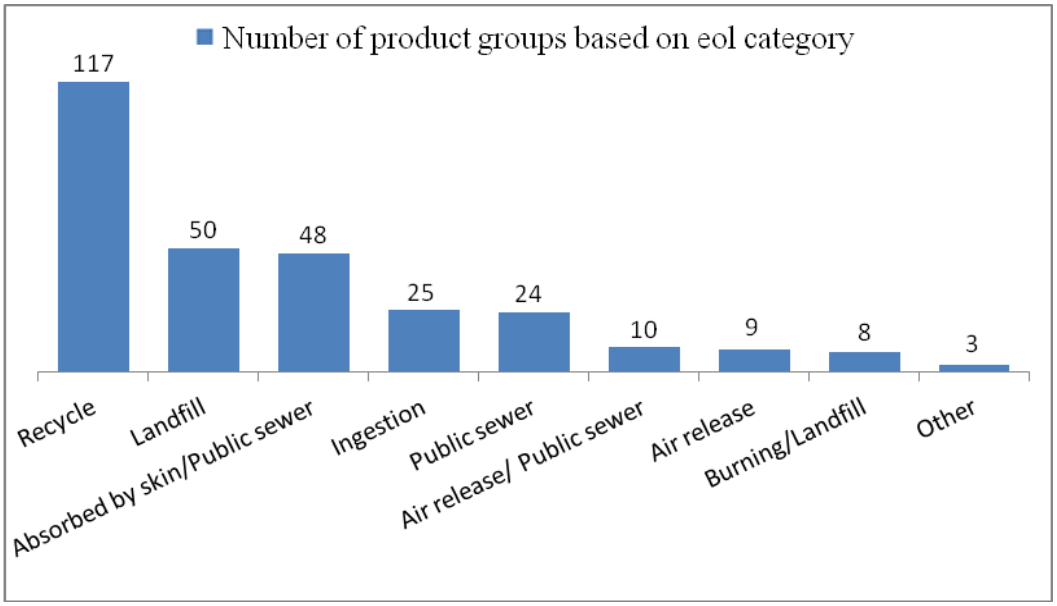

Figure 2.2 EOL nano-product list distribution with consolidation of similar products (294 total).

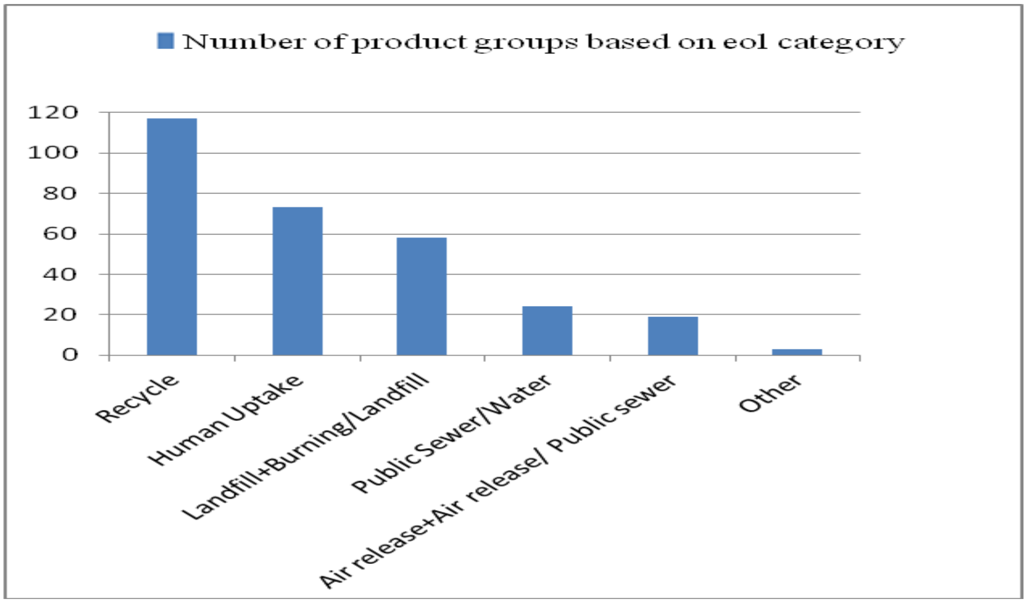

Figure 2.3 The recombined nano product EOL list distribution (294 total)

As a further means of interpreting to current nanoproduct EOL fate, Figure 2.3 makes further refinements by combing the two categories, absorbed by skin and ingestion into one category called direct human uptake. Landfill and burning/landfill are similarly combined to one category, as are air release and air release/public sewer. In this form, we see that the potential for recycle is still the largest EOL of the current nano-products (40%). The body uptake by human and partly by animals is the second largest (25%). Landfill is the third (20%) while discarding to water, to air, and other as the smallest EOL categories (8%, 6%, and 1%, respectively).

Interpreting these EOL data it would appear that the potential to recycle post-consumer products including the nano-material content is reasonably high. This potential is based on the large percent of nano-products (40 %) that are in products currently recycled for equivalent non-nano-products. However at this time only few citations could be found to document any post-consumer nano-product recycling (Gungor and Gupta, 1998; Piotrowska et al., 2009; Olapiriyakul and Caudill 2009; Asmatulu et al., 2010; Lloyd and Lave, 2003)

This low number of citations may be related to the lack of development for recycling infrastructure technology or the cost. The recycling technology for nano-products might benefit by developing technology based on the distribution of nano-materials found in the PEN CPI (Berube, et. al., 2010), which primarily was 61% silver, 21% carbon, 7% gold, and 6% iron. The EOL fate of direct uptake by human is characterized for about 25% of nano-products. Air and water exposures are together the lowest EOL fate of nano-products.

The large fraction of nanoproducts that are generally in the recycle EOL category was unanticipated. This discovery may be considered unexpected by the nanoproduct research community because when searching for research and publications as a reflection of how the public, industry, or academics view recycling, there are relatively few citations. These citations are listed above and reviewed in the Introduction part of this chapter. In general, there are very few publications found in a literature search regarding nanoproduct recycle, thus reflecting the lack of understanding of the potential relative EOL fate of this nanoproduct category.

Additional implications or research that may be derived from these findings relate to the question of how nanoproducts differ from similar non-nanoproducts. Are the nano and non-nano products different in some undiscovered way with respect to recycling or reuse? Another issue from identifying the role of recycling as a non-nanoproduct EOL is whether the nano materials add value to recycling since these materials are generally more costly, or nanomaterials impede recycling for other chemical or material reasons.

Analyzing these EOL results also identifies that less than 6% of these products fit into the human impact of product inhalation category (small particles) perceived as the primary concern for nanoproducts. This may have a research impact that differs from current research expectations for nanoproducts. That is, future research priority should account for the relative size or distribution of the actual marketed products and the EOL categories from this study. In other words, do we understand adequately the EOL of the largest volume of nanoproducts in the market today?

An effort to reconcile future research to EOL implications might need to develop more effort on dermal and direct ingestion implications of nanoproducts. In addition, more emphasis on whether nanoproducts have some distinctive behavior or fate in landfills (this study did not theorize such differences, but only connects the need for research to the distribution of EOL alternatives for nanoproducts).

This EOL analysis of nanoproducts, (supplementary information Table 2.1), also produces insights into the current nature of these products, as catalogued in the PEN CPI list, 2010. After consolidation of the 1014 nanoproducts into distinct product groups (294) there is a range of listed products per distinct group or category. The average number of similar product per group was thus 3-4 with many having only one product. However, there are implications from examining those groups with more than ten products per group, Table 2.1. These more populated groups reflect a response to the market as new manufacturers use nanomaterials to create these products. The largest group by far is clothing. This is followed by dermal-related products of sunscreen, moisturizer, and anti-aging products. The third largest group was interestingly hair irons. Bicycle and tennis equipment was another large group. All the other entries on Table 2.1 are in the 10-15 products per group range.

TABLE 2.1 MAJOR NANOPRODUCT DISTRIBUTION DERIVED FROM THE PEN CPI LIST, 2010

Product category encompassing multiple nanoproducts found in the PEN CPI list	Number of products per category
Clothes	137
Sunscreen	35
Hair iron	28
Body lotion moisturizing	22
Bicycle products	21
Anti-aging cream	17
Tennis racket	16
Toothpaste	14
Health supplements	13
Computer processors	13
Beauty soap	11
OLED screen	10
Air purifier	10
Hair dryer	10

The results shown in these Figures and Tables can be used as a benchmark for nano-products if a similar catalog for PEN CPI is made in five years (2015). Again, the authors caution that these results are for the fuzzy profile of nano-products given by the current PEN CPI, but do provide a general magnitude of EOL understanding to stimulate further development of solutions for EOL environmental improvement.

2.5 LIMITATIONS AND FUTURE RESEARCH

It is recognized that the numbers and category sizes shown in the research are approximate because of the limitation of any comprehensive catalogue for nanoproducts (Berube, et. al., 2010). This concern about actual presence in the marketplace is not a significant factor in this analysis as the products listed are still in some existence and do demonstrate the diversity if nanoproducts. Additionally, we have required each given product to best fit into a single category. The recycling category is, at best, the potential for reuse since no economic analysis or infrastructure development were separately studied at this time. Instead, analogous non-nano-product recycling was used for this EOL category. While the potential implications of nano-product recycle are noticeable, the actual effect of nanomaterials on recycling systems could not be inferred from these preliminary results. Future demand for recycling technology for nano-products may be stimulated by the actual market size of individual products or the potential value of these nanomaterials, but neither could be interpreted from this first stage study of EOL for nano-products. Finally, the actual market size of any given nanoproduct was not used to weigh the EOL product computations.

Future research is intended to search for recycling firms in operation that have been actually recycling nano-products by virtue of the product recycled. Also remaining work should incorporate with the other life cycle stages of nano-products, such as cradle-to-gate and gate-to-gate that can provide an understanding of entire life cycle concept of environmental impacts. The information herein may improve the ability to do a broader nanoproduct risk analysis by those with expertise in that field. Another future research goal would be to look in-depth at the top recycling categories, Table 2.1, as to what technology exists or needs to be developed to recover nanomaterials by recycling as an enhancement over just product recycle. These new topics might also address whether the nanomaterials recovery is economically feasible or might entail risk.

2.6 CONCLUSIONS

Nanomaterials have outstanding properties (e.g., mechanical, electrical, optical, magnetic, and thermal) and are used for a number of different applications. Although nanomaterials research and development have been growing for over a decade, life cycle analysis of these materials has not yet been widely studied. In this study, we focus on the EOL stage of life cycle analysis, as we categorized nano-products in different groups based on the final destination after use. Within the life cycle analysis framework, exploring EOL of the nano-products offers benefits from considering environmental sustainability impacts, such as energy and material consumed. This study confirms that current nano-products appear to have high recycle potential which leads to use less natural resources, and also spends less energy to obtain high technology products again. The largest potential EOL fate was found to be recyclability, however little literature appears to have evolved around nano-product recycling. At lower frequency is human uptake and then landfill. Release to water and air are much less likely EOL fates for current nano-products. In conclusion, recycling and reuse of the nano-products open new possibilities for nanomaterials sustainability. Further research is needed to identify availability of recycling infrastructures and cost-benefit analysis of recycling nano-products.

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APPENDIX-1.1: EOL CATEGORIZATION FOR PEN CPI LIST OF NANO-PRODUCTS

	End of Life Category	Product	Number of similar products combined	Application	Where nano material is used
1	Recycle	Batteries	4	Energy	Contains nano-titinate material or nano-phosphate
2	Recycle	Air Purifier	10	Cleaning air	Catalyst is coated by nano
3	Recycle	Air Conditioner	3	Cooling air	Silver Nano Filter and Evaporator
4	Recycle	Refrigerator	7	Cooling food	Nano-size silver particles coat the interior of refrigerator
5	Recycle	Hair Dryer	10	Drying hair	Nano-silver infused ceramic grill and handle
6	Recycle	Vacuum Cleaner	7	Cleaning carpet etc.	Nano-silver coating used in the dust bin, pre motor filter, and post motor filter.
7	Recycle	Humidifiers	2	Providing humid environment	Nano silver technology applied to the water tank surfaces.
8	Recycle	Hand Dryer	1	Drying hand	Ag(Silver) nano filter
9	Recycle	Watercraft	7	Vehicle on water.	High strength material reduces the weight of the hull and decks
10	Recycle	Washing Machine	4	Washing clothes	Using Nano Poly Technology in Pulsator & Tub U
11	Recycle	Tire	2	Part of the car	Micro-flexible compound developed using nanotechnology

	End of Life Category	Product	Number of similar products combined	Application	Where nano material is used
12	Recycle	Titanium dioxide Coating	2	Plastics applications including films, packaging etc.	Made by ultrafine titanium dioxide
13	Recycle	Thin Film Coating on Polyester	2	Ultra thin coating	Entire product is coated by ultra thin film.
14	Recycle	Car Air Purifier	1	Decomposes allergens, kills bacteria	Utilized from nano TiO2
15	Recycle	Lubricant	1	Lubricating	No information accessible.
16	Recycle	Audio (Cassette)	1	Playing cassette	Made of nanostructured polymer films
17	Recycle	Water tap, Watch chain & Lock etc.	3	Coating for antibacterial product	Outside coated for preventing bacteria
18	Recycle	Camera	2	Taking picture	Lenses are nano coated(antireflectant)
19	Recycle	Flash Memory	7	Data storage	Entire material is nanosize
20	Recycle	Processors	13	Running the application	Entire material is nanosize
21	Recycle	Hard Disc Drive	1	Computer part	30-50 nanometer size recording heads
22	Recycle	Wireless Laser Mouse	3	Moving icon on the screen	Outside is coated with a TiO2 and Ag nano-particles.
23	Recycle	Wireless Keyboard	3	Writing	Coated with a titanium dioxide and silver nano-particle
24	Recycle	Notebooks	1	Storing data	Silver nanocoating on the keyboard and palm rest

	End of Life Category	**Product**	**Number of similar products combined**	**Application**	**Where nano material is used**
25	Recycle	Screen (OLED)	10	Showing images	Made of nanostructured polymer films
26	Recycle	Mobile Phone	2	Communication	Outside is coated with a layer of silver nano ions
27	Recycle	Stream Light	2	Illumination	Nanotechnology cell battery technology
28	Recycle	Television	1	Watching	Utilized from Nanotechnology (Screen)
29	Recycle	Game (Xbox)	1	Playing game	Transistors fabricated by nanometer silicon on insulator technology
30	Recycle	Pan	1	Cooking food	Nano ceramic non-stick coating
31	Recycle	Cutting Board	2	Cutting vegetables	Cutting surface with nano-silver coating
32	Recycle	Tea Pot	2	Making tea	Inside and outside coated by nanomaterials
33	Recycle	Nanofilms for Glass Bake Ware	1	Providing non-stick bake ware	Outside is nano-coated
34	Recycle	Guitar Strings	1	Balanced tone	Micro thin coating
35	Recycle	Beer/Water Bottle	3	Carrying beer/water	A plastic imbued with clay nano-particles
36	Recycle	Food Storage Containers	3	Storing food	Product contains nano-silver particles
37	Recycle	Baby Mug Cup	2	Storing milk	Product contains nano-silver particles

	End of Life Category	**Product**	**Number of similar products combined**	**Application**	**Where nano material is used**
38	Recycle	Antibacterial Make-up Instrument	1	Makeup instrument	Nano silver coating on material
39	Recycle	Bicycle	3	Transportation	Frame is made out of carbon nanotube
40	Recycle	Bicycle Products	21	Road bar, seat post etc.	CNT is added to strengthen and toughen the resin matrix.
41	Recycle	Bowling Ball	2	Playing bowling	Applied nano-carbon particle technology
42	Recycle	Golf /Tennis ball	2	Playing golf	Nano-enhanced polymer companion ball
43	Recycle	Crampon	1	Sport product	Steel alloy and nano used
44	Recycle	Cordless Power-tool Set	1	Drilling etc.	Battery cathode based on phosphate nano-crystals
45	Recycle	Self Cleaning Glass and Ceramic	6	Keep the glass free from organic dirt	Outside is nanocoated
46	Recycle	Cultured Diamonds	1	Jewelry	Grown with the CVD method
47	Recycle	Kitchen Ware	2	Using in the kitchen	Nano-silver coating
48	Recycle	Shoe Locker	3	Sterilizing the shoe	Nano silver technology is used(machine)
49	Recycle	The Handler	1	Storage	Rubber components are combined with silver nano particles
50	Recycle	Mattress	1	Sleeping	Contains nano whisker
51	Recycle	Wood Sealant	5	Applied on deck	Particles are nano-sized

	End of Life Category	Product	Number of similar products combined	Application	Where nano material is used
52	Recycle	Swim Suit	4	Service time increasing	Nanotechnology applied to the suit
53	Recycle	Ice Axe	3	Stronger and light sport product	Nanoflex steel alloy reinforcements on the pick and spike
54	Recycle	Sensor	1	Converts an optical image to an electric signal	Mobile phones, automobile sensors, and digital applications
55	Recycle	Hockey Sticks	2	Playing hockey	Used carbon nano tube
56	Recycle	Baseball Bat	2	Stronger and light sport product	Nano composite shell bat
57	Recycle	Fishing Lures	1	Attracting fish	Nano coated
58	Recycle	Balaclava, Head Cover, etc.	1	Protecting head	Nano silver technology used
59	Recycle	Shooters Gloves	1	Protecting hand	Nano silver technology used
60	Recycle	Antibacterial Nano Chopsticks	1	Eating utensils	Far-infrared nano material composite materials is used
61	Recycle	Fishing Rod	1	Strong and light rod	Nano titanium quartz applied
62	Recycle	Baby carriage	1	Carrying	Using nano silver
63	Recycle	Foot massager	1	Massaging foot	Inside is coated with nanosized silver particles
64	Recycle	Hearing Instrument	2	Hearing aid	Nanocoated surface
65	Recycle	Automotive exterior	2	Uses for sail panel, centre bridge etc.	Nano composite material is used for specified parts.

	End of Life Category	Product	Number of similar products combined	Application	Where nano material is used
66	Recycle	Luggage	8	Providing light &strong luggage	Used Nano-Tex® fabric
67	Recycle	Izor Skis	1	Skiing	Carbon nano fiber used for stress points.
68	Recycle	Tennis/ badminton/ squash Racket	16	Playing tennis	Carbon nanotubes are used to stiffen key areas of the racquet head and shaft
69	Recycle	Engine Oil	2	Lubricates rotating surfaces	Utilized from nanotechnology
70	Recycle	Blankets and Throws	1	Use on chair and couch.	No information accessible
71	Recycle	Smart Bed	3	Sleeping (pet)	Nanotechnology-based textile is used
72	Recycle	Equine Products for Horse	1	Covering horse	Nano technology applied stable and antibacterial blanket.
73	Recycle	Aqua Toy	1	Playing	Nanotech coating
74	Recycle	Mercedes Benz	1	Paint finish	Contains nano-particles
75	Recycle	Surfboard	1	Surfing	It is coated with resin and titanium nano-particles
76	Recycle	Snowboard	1	Snowboarding	Nano high speed graphite base
77	Recycle	Protective Garments	1	Protecting head	Titanium, carbon fiber or high-strength steel
78	Recycle	Plush Toy	3	Playing	Silver nano-particles are added

	End of Life Category	**Product**	**Number of similar products combined**	**Application**	**Where nano material is used**
79	Recycle	Clothes (fabric, pant, socks, shirt, dress, sheet set, towel etc)	137	Wearing	Inside of the product (e.g. On the yarn)
80	Recycle	Golf Shaft	6	Part of golf racket	Shaft is sprayed or dipped in nanocomposite
81	Recycle	Binocular	1	Magnifying objects	Nanocoating on glass surface
82	Recycle	Anti-bacterial Pet Food Container	1	Antibacterial food containers	Nano silver coating
83	Recycle	Toilets	1	Disposal of the bodily wastes	In the ceramic material(produce smooth surface)
84	Recycle	Electronic Bidet	3	Nano-silver nozzle	Nozzle is coated
85	Recycle	Nanowax for Skis	2	Used for coating surface	Products made using chemical nanotechnology
86	Recycle	Permanent Head Gasket Block Repair	1	Repairing	Uses nano-particles
87	Recycle	Wristband	3	Supporting wrist	Contains nano-particles of bamboo-charcoal
88	Recycle	Shoe Sealant	2	Applied on shoe	Shoe seal consists of nano particles
89	Recycle	Earmuffs	1	Protecting ear	Nanotechnology applied to each fiber

	End of Life Category	Product	Number of similar products combined	Application	Where nano material is used
90	Recycle	Nano-Polish for Inside of the Car	3	Polishing	Nanotechnology formula is used
91	Recycle	Hair Iron	28	Curling or straightening the hair	Nano-silver is sprayed on the whole surface of the body
92	Recycle	Nano-ceramic Coating	1	Nanoceramic coating on clean metal substrates.	No information accessible.
93	Recycle	Laptop	1	On cooling fan	Cooling fan is coated with CNT
94	Recycle	Ultrasonic Washer	1	Washing vegetables (Plastic Machine)	Contains nanosilver particles
95	Recycle	Anti Bacterial Sealant	1	Use in refrigerator	No information accessible.
96	Recycle	Plastic Seal	2	Applied on plastics	Consist of nano-particles
97	Recycle	Stainless Steel Seal	1	Applied on metal	No information accessible.
98	Recycle	Functional Coating	1	Applied on PE, rubber, PVC.	Utilized from nanotechnology
99	Recycle	Functional Coating (Permanent)	1	Non-stick coating on glass, ceramics, metals or polymers	Utilized from nanotechnology
100	Recycle	Air sanitizer	2	Sanitizing air (machine)	Nano-silver technology in the dirt cup of the hand vac.
101	Recycle	Aircraft	1	Airframe and engine	Consist of carbon nano composite.

	End of Life Category	Product	Number of similar products combined	Application	Where nano material is used
102	Recycle	Salad Bowl	1	Meals	Contains nanosilver particles
103	Recycle	Truck Battery	1	Battery	Ceramic nanomaterials
104	Recycle	Nano Hand Bag	1	Fashion	Nano knit wool handbag
105	Recycle	Metal Alloy	1	Sporting products (skating blades)	No information accessible.
106	Recycle	Paper Coating	1	On paper	Nano composite coating on paper
107	Recycle	Car Catalyst	2	Use in car, truck	Metallic ions of palladium used.
108	Recycle	Nanofibril	1	Clothing	Nanotechnology is used
109	Recycle	Oil cleaner	1	Catalytic device for cleaning oil	Made out of nanoceramic (Machine)
110	Recycle	Pedicure Chair	1	Sitting	Contains nano silver
111	Recycle	Anti-microbial Fiber	1	Use for any kind textile	Contains nano silver (Nano silver is rarely dissolving)
112	Recycle	Natural Nanoclay	1	Plastic industry	Contains nano particles
113	Recycle	Nano Fuel Saver	1	Installing in car	Tube impregnated with nano-particles
114	Recycle	Fibril Nanotubes	1	Fibril nanotubes used to make plastic compound.	Contains nanotubes(use for fenders, door handles, mirror housings)
115	Recycle	Garden and Recreational Oil	1	Uses for motorcycles, snowmobiles, chain saws etc.	No information accessible.

	End of Life Category	Product	Number of similar products combined	Application	Where nano material is used
116	Recycle	Motor Oil	3	Uses for regular motor	No information accessible.
117	Recycle	Nano-Silver Antimicrobial Plastic Granule	1	Such as telephone in hospital	Consist of nanosilver particles
118	Ingestion	Toothpaste	14	Applied on teeth	Contains nano-silver
119	Ingestion	Slim Shake	1	Helping to slim	Contains nanocluster
120	Ingestion	Tea	1	Drinking	Contains selenium
121	Ingestion	Espresso Maker	2	Making espresso	Inside of the machine coated by silver ions
122	Ingestion	Liquid Supplement	2	Support Body	Nano-sized self-assembled liquid structures
123	Ingestion	Health support for immune system	13	Supporting immune system	Utilizes nanotechnology to produce supplement
124	Ingestion	Nano Oxygen Supply	2	Activation of oxygen, pH salinity, adjustment of water	Contains 20% nanomaterials
125	Ingestion	Canola Active oil	1	Put in food	Nano-sized self assembled structured liquids
126	Ingestion	Muscle developer	2	Develop muscle /intake to body	Nanomolecular rapid explosion technology is used
127	Ingestion	Vitamin C	1	Heart, liver, kidney health	Vitamin C are about 300 to 400 nanometers in diameter

	End of Life Category	Product	Number of similar products combined	Application	Where nano material is used
128	Ingestion	Vitamin, vitamin B-12,vitamin D	4	Health support (Spray)	Nano-ceutical delivery system
129	Ingestion	Artichoke Nano-clusters	1	Nourish immune system	Nanosize powder that combines with nutritional supplements
130	Ingestion	Calcium / Magnesium pill	2	Health support	Contains nano particles of calcium and magnesium
131	Ingestion	Nanocluster	4	Reduce lactic acid during exercise	Contains nanocolloidal silicate mineral
132	Ingestion	Nanoslim (pill)	2	Help to slim	Ingredients are micron size
133	Ingestion	Anti-microbial Pain Supplement	1	Reduction in pain	Product use special antioxidation and antimicrobial nano silver
134	Ingestion	Glycemic Supplement	1	Balanced blood sugar levels	Utilized nanotechnology to produce supplement
135	Ingestion	Humic and fulvic acid	1	Helps to body take out toxins and fungi	Utilized nanotechnology to produce it
136	Ingestion	Colloidal Silver Liquid	6	Dietary supplement	Contains nanosize silver particles
137	Ingestion	Maternal Water	1	Drinking	Uses nano colloidal silver ion
138	Ingestion	Joint Support	1	Improve the bioavailability of hyaluronic acid to joint support	No information accessible.

	End of Life Category	Product	Number of similar products combined	Application	Where nano material is used
139	Ingestion	Tooth Powder	1	Applied on to teeth	Inside of the product
140	Ingestion	Colloidal iridium, Copper, Gold, Palladium, Platinum, Titanium and Zinc Mineral Supplement	9	Health support	Contains iridium or copper or gold nano particles.
141	Ingestion	Feed Powder	1	Mixing with the animal food	No information accessible.
142	Ingestion	Anti-Aging Nutrients	1	Decreases aging symptoms	No information accessible.
143	Absorbed by skin/Public sewer	Nanometer-Silver Foam Condom	1	Birth control foam	Contains nano silver
144	Absorbed by skin/Public sewer	Silver Cream	1	Use in healing minor burns.	Contains colloidal silver
145	Absorbed by skin/Public sewer	Anti-Aging Nutrients (Cream)	17	Applied on skin	Contains nano-spheres
146	Absorbed by skin/Public sewer	Sun Screen	35	Protection from sun	Nano-particles of zinc oxide or titanium dioxide
147	Absorbed by skin/Public sewer (scalp)	Hair Growth Solution	6	Re-growing hair/applied to the scalp	Contains superoxide dismutase

	End of Life Category	Product	Number of similar products combined	Application	Where nano material is used
148	Absorbed by skin/Public sewer	Hair Serum	3	Protects color-treated hair	Molecular nanotechnology color longevity formula
149	Absorbed by skin/Public sewer	Pet Spray	1	Applied to the pet body	Contains nano-silver
150	Absorbed by skin/Public sewer	Deodorant Powder Spray	1	Odor control	Each granule contains countless nano-size pores
151	Absorbed by skin/Public sewer	Whitening Lotion	4	Enhances whiteness of skin	Nano application is used
152	Absorbed by skin/Public sewer	Body Wash	1	Cleaning and moisturizing	Contains nanocluster
153	Absorbed by skin/Public sewer	Tanning Gel	2	Tanning	Contains nano-capsules of pure vitamin E
154	Absorbed by skin/Public sewer	Nano Breast Cream	1	Promotes development of the alveoli and lobules	In the product
155	Absorbed by skin/Public sewer	Alumina powders	1	Makeup products	Contains nanopowder
156	Absorbed by skin/Public sewer	Nano-Cream for Neurodermatitic Skin	3	Protection against oxidative impact of ultra violet light	Contains nano-particles
157	Absorbed by skin/Public sewer	Body and Hand Lotion-Moisturizer	22	Moisturizing	Uses nanotechnology to make the molecules very small

	End of Life Category	Product	Number of similar products combined	Application	Where nano material is used
158	Absorbed by skin/Public sewer	Cleaning Gel	1	Remove makeup and dead cells	Contains nano ZnO
159	Absorbed by skin/Public sewer	Cellulite Cream	1	Reduce the cellulite	Nano Technology delivery system is used
160	Absorbed by skin/Public sewer	Nano Skin Rejuvenator	6	Reducing aging effect	Nano-sized formula
161	Absorbed by skin/Public sewer	Hydrating Body Mist	6	Refreshing body	Ultra-light nano-emulsion hydrating particles prolong fragrance
162	Absorbed by skin/Public sewer	Acne Lotion	4	Clears existing acne	Contains nanoparticles
163	Absorbed by skin/Public sewer	Mascara	1	Make up	Utilized from nanotechnology
164	Absorbed by skin/Public sewer	Liquid Foundation	2	Make up	Nano-particles in liquid foundation
165	Absorbed by skin/Public sewer	Lip Moisturizer/ Paint	3	Make up	Contains nanosphere-delivered peptides or zinc oxide particles
166	Absorbed by skin/Public sewer	Serum and Ampoule for Skin	9	Renewing, moisturizing skin	Contains pure carbon cage molecules.
167	Absorbed by skin/Public sewer	Beauty Soap	11	Cleaning skin	Contains nano silver
168	Absorbed by skin/Public sewer	Whitening Mask	3	Whitening body	Contains nano colloidal silver

	End of Life Category	Product	Number of similar products combined	Application	Where nano material is used
169	Absorbed by skin/Public sewer	Hair polish	1	Applied on hair	No information accessible
170	Absorbed by skin/Public sewer	Conditioner	4	Applied on hair	Used nanospheres.
171	Absorbed by skin/Public sewer	Mosquito Repellent Spray	1	Protecting body	Nano technology applied
172	Absorbed by skin/Public sewer	Shampoo	6	Applied on hair	Uses guava molecular nanotechnology color longevity formula
173	Absorbed by skin/Public sewer	Joint & Muscle Pain Relief Cream	1	Reduce pain/applied on to skin	Microscopic capsule is used(nanotech delivery system used)
174	Absorbed by skin/Public sewer	Anti-microbial Gel	2	Applied on skin	Contains nano-silver
175	Absorbed by skin/Public sewer	Face Cleanser	4	Applied on skin	Contains nano-silver
176	Absorbed by skin/Public sewer	Hair Style Cream	7	Curling hair	Nanotechnology color longevity formula applied
177	Absorbed by skin/Public sewer	Facial Spray	2	Hydrating effect	Contains nano copper
178	Absorbed by skin/Public sewer	Pet Shampoo	1	Applied to the pet body	Contains nano-silver
179	Absorbed by skin/Public sewer	Ionic Steamer	1	For face	Creates ion steam particles that are very small, thus can moisturize skin very well.

	End of Life Category	Product	Number of similar products combined	Application	Where nano material is used
180	Absorb by skin/Public sewer	Sunscreen Powder	1	Applied on skin	Contains 25% titanium dioxide and 20% zinc oxide
181	Absorb by skin/Public sewer	Anti-bacterial Solution	6	Applied to the skin	Consists of nano-silver solution
182	Absorbed by skin/Public sewer	Hair Spray	2	Applied on hair	Contains nanofibre
183	Absorbed by skin/Public sewer	Hair Transplant Powder	1	Applied on scalp	Contains nanofibre
184	Absorbed by skin/Public sewer	Hair Nourish	1	Cleans the cuticle and the scalp	Consist of nanosilver particles
185	Absorb by skin/Public sewer	Self Heating Cream	1	Applied on hands	No information accessible.
186	Absorb by skin/Public sewer	Cuticle Lotion	1	Applied on fingers and toes	Contains nanospheres
187	Absorb by skin/Public sewer	Cosmetic	14	Applied on skin	Using nanocomplexes of proteins (anti-aging cream, cleanser for acne, essence and mask).
188	Absorb by skin/Public sewer	Foot Odor Eliminating Spray/ Powder	1	Applied on foot	Contains nano ZnO
189	Absorb by skin/Public sewer	Hand nail moisturizing serum	1	Applied on foot	Contains nano ZnO

	End of Life Category	Product	Number of similar products combined	Application	Where nano material is used
190	Absorbed by skin/Public sewer	Fullerene	7	Cosmetic applications	Nano material
191	Burning/ Landfill	Full Body Suit for Radiation	1	Protecting body from radiation	Utilized from nanotechnology
192	Burning/ Landfill	NanoMask	2	Protection from harmful airborne contaminants	Utilizes nano-particle enhanced filters
193	Burning/ Landfill	Wound Dressings	1	Skin contact layer/bandage	Contains nanocrystalline silver coating
194	Burning/ Landfill	Back Supporter	2	Protecting back	Nano-scale ceramic is used in the product
195	Burning/ Landfill	Elbow Supporter	2	Protecting elbow	Contains nano-particles of bamboo-charcoal
196	Burning/ Landfill	Pregnancy Test	1	Defining whether or not women are pregnant	Gold nano-particles are used for defining the color change
197	Burning/ Landfill	Epoxy Coatings	1	Encapsulation of asbestos, marine application.	Polymer chemistry combined with nano technologies.
198	Burning/ Landfill	Knee Guard	2	Protecting knee	Contains nano-particles of bamboo-charcoal
199	Public sewer	Algae Inhibitor	1	Cleaning fish tank	Using nanotechnology
200	Public sewer	Car Polisher	8	Shining car	Contains nano-particles
201	Public sewer	Car Wash	8	Cleaning car	Used nanotechnology formula

	End of Life Category	Product	Number of similar products combined	Application	Where nano material is used
202	Public sewer	Degreaser& Floor Cleaner	4	Cleaning	In the liquid (unknown)
203	Public sewer	Cleaning agent	2	Cleaning the kitchen	Inside of the product contains nano
204	Public sewer	Fabric Softener	3	Soften fabric	Inside of the product (nano-silver added)
205	Public sewer	Cleaning Agent	2	Remove any pesticide residues on vegetable	Nano micelle product
206	Public sewer	Mold & Mildew Stain Remover /Concrete /All Purpose Cleaner	4	Use into the Pressure washer	Inside of the product
207	Public sewer	Nano-Clean Liquid	3	Cleaning	Contains titanium dioxide
208	Public sewer	Fabric (Laundry Detergent)	2	Applied on clothes	Inside of the product
209	Public sewer	Wood Cleaner	1	Cleaning wood	No information accessible
210	Public sewer	Nano Protectant for Car	2	UV protectant, cleaning (interior)	Contains nano-sized particles
211	Public sewer	Cleaning Kit (Nano Rim Sealant)	5	Wheel sealant	Contains nano-particles
212	Public sewer	Wheel Cleaner	3	Cleaning wheel	Nano-tech formula

	End of Life Category	Product	Number of similar products combined	Application	Where nano material is used
213	Public sewer	Laundry Pure Cleaning Process	2	Upgrade washing machines	Uses nano technology to electrolyze 99.99% pure silver probes during the wash and rinse cycles.
214	Public sewer	Smart Silver	2	Applied on yarn	Consist of nanosilver particles
215	Public sewer	Anti-bacterial Agent	4	Powder using in textile, rubber etc.	Particles are nano-sized
216	Public sewer	Colloidal nanosilver	5	Applies on fabric	Consist of nano-particles
217	Public sewer	Tire Cleaner	1	Applied on tire	No information accessible.
218	Public sewer	Protect Cleaner	5	Ceramic, glass, plastic, mold, surface.	Contains nanoparticles
219	Public sewer	Colloidal Cleaner	1	Automotive parts cleaning, hotels, hospitals, health care centers etc.	Utilized from nanotechnology
220	Public sewer	Self Cleaning Coating	2	Fabric	Nanometer titanium dioxide, nanometer zinc oxide
221	Public sewer	Leather Care	1	Applied on leather shoes	Nanotechnology is used
222	Public sewer	Windshield Treatment	1	Sealing mirror and glass(It last 1 year)	Consist of nano-particles
223	Landfill	Anti-Static Silicon Dioxide Coating	1	Applied on any hard surface	Utilizing the principles of nanotechnology

	End of Life Category	Product	Number of similar products combined	Application	Where nano material is used
224	Landfill	Aluminum Foil	1	Containing food	Al foil and carbon can be embedded in a glass matrix to make non-stick coating.
225	Landfill	Tooth Brush Sterilizer & Bathroom Ionizer	1	Cleaning tooth brush (machine)	Nano-silver technology adopted for sterilization
226	Landfill	Nano Pocket Umbrella	2	Protect from rain	Nano structure is used
227	Landfill	Wet Wipes	3	Prevent skin troubles due to bacteria	Contains natural silver manufactured at a nanoscale
228	Landfill	Little Dog Bark Collar	1	A strap around an animal's neck	Used Nanotechnology
229	Landfill	Photo Paper	1	Photographic prints	Ceramic coated
230	Landfill	Water Filter	6	Filter viruses and others from water	Nano-fibers are holding carbon powder
231	Landfill	Odor Removal Sticker	2	Removing odor	Nano technology applied
232	Landfill	Ag Silver Conductive Ink	3	Writing	Contains nano-silver
233	Landfill	Posture Sensor for Body	1	Providing right posture	Nano-sensor
234	Landfill	Insulation	1	Used to reduce the rate of heat transfer	Nanometer-sized cells
235	Landfill	Nano Pacifier	1	Stops baby crying	Contains nano-silver

	End of Life Category	Product	Number of similar products combined	Application	Where nano material is used
236	Landfill	Nano Shoe Pads	6	Keeping clean	Contains nanopowder
237	Landfill	Silver Slippers	1	Wearing	Contains ultra-fine silver nano-particles
238	Landfill	Face Brushes	1	Cleaning face	Contains 6% micronized zinc oxide & 6% micronized titanium dioxide
239	Landfill	Soft Cloth Mask	6	Face mask	Containing nano-particles of bamboo-charcoal
240	Landfill	Razor	6	Shaving	Replacement Foils coated by nanosilver
241	Landfill	Hair Setter	2	Shaping hair	Nano ceramic produces far-infrared heat
242	Landfill	Epilator	1	Cleaning hair	Depilation head with nano silver
243	Landfill	Support Pillow	6	Supporting neck	Ultra-fine silver particles
244	Landfill	Air Sanitizer, Nano Silver Photo Catalyst	4	Liquid antibacterial/ air sanitizer	Made of TiO2, nano zinc, nanometer Ag, SiO2 and modifying resin
245	Landfill	Disposable Shaver	1	Removing hair	Nano-silver coated foils
246	Landfill	Nano Glue	1	Applied on different kind of materials	Inside of the product
247	Landfill	Hot Ice Thermal Patch	5	Applied to the body part	Contains a nano-scale organic molecular antenna

	End of Life Category	**Product**	**Number of similar products combined**	**Application**	**Where nano material is used**
248	Landfill	Nano liquid (Fill up Material)	1	Revives old connections, improves new ones.	Super-micro particle made by two material pure gold and pure silver
249	Landfill	Water Filter Cartridge	2	Cleaning water	These include nanofinely granulated copper and zinc alloys.
250	Landfill	Anti Fog Cleaning Cloth	2	Cleaning lens	Nano-technology based anti-fogging coating & cleaning agent
251	Landfill	Air Filter	8	Air filtration	Made out of porous nanofilter media
252	Landfill	Water Purifier	6	Supplies bacteria-free water	Nano Silver Ceramic Filter
253	Landfill	Baby Bottle Brush	1	Cleaning	Uses of Nano Silver technology
254	Landfill	Antimicrobial Paint Supplement	1	Hospital, restaurant and school.	Utilized from antioxidation and antimicrobial nano silver
255	Landfill	Cigarette Filter	1	Use in filter	Made out of nano-fiber
256	Landfill	Tooth brush	6	Cleaning teeth	Contains nano-silver
257	Landfill	Artificial Teeth Cleaner	1	cleaning artificial teeth	Nano-silver technology applied
258	Landfill	Hair Brushes	6	Brushing hair	Contains nano-silver
269	Landfill	Ear Protector	1	Protecting ear	Contains nano-silver (inside)
260	Landfill	Micro Fiber Cloth	1	Cleaning	Fiber cloth impregnated with long lasting sealed nano

	End of Life Category	Product	Number of similar products combined	Application	Where nano material is used
261	Landfill	Respirators	2	Protecting person from dusts, fumes	Coated with anti-virus solution using nano-particle technology
262	Landfill	Adhesive for Burger Containers	1	Starch adhesives	Made out biopolymer nano-spheres.
263	Landfill	Plastic Wrap/Food Container	3	Storage of food	ZnO Products/nano silver
264	Landfill	Pencil Lead	1	Writing	Fragrance is encapsulated using nanotechnology
265	Landfill	Homeo-pathic Medicines (Energy Patch)	3	Increase energy, supports breathing & stamina	No information accessible
266	Landfill	Beverage storage	1	Wine container	No information accessible.
267	Landfill	Safety Glow Flare	1	Glows	Consist of nano particles
268	Landfill	Teeth Developer	1	Use for baby teeth	Contains nanosize silver particles
279	Landfill	Nano Wiper	1	Cleaning the car	180,000 fibers per square inch. Fibers are nanosize.
270	Landfill	Wipe	3	Cleaning glass, ceramic,plastic	No information accessible.
271	Landfill	Eco-Coating	1	Plastic, paper, metal, electronic	Nanotechnology is used
272	Landfill	Molding Technology	1	Aerospace, military, biomedical	Light weight magnesium sheet with nanometer microstructures are using

	End of Life Category	**Product**	**Number of similar products combined**	**Application**	**Where nano material is used**
273	Air release	Ionic Silver Stick	1	Use in humidifiers	Consists of a silver core and a nanostructure surface
274	Air release	Fuel Borne Catalyst	2	Increase fuel economy	Product contains cerium oxide (Liquid)
275	Air release	Odor Eliminator	5	Eliminating odor(spray)	Inside of the product
276	Air release	Anti-fog and Regular Glass Cleaner	5	Cleaner	Contains nano-sized particles
277	Air release	Oven & Barbecue Cleaning Spray	1	Cleaning oven	Consist of nano-particles
278	Air release	Bathroom/ Kitchen Mist	3	Spray on surface	Consist of 15 nanometer Alumina-silica
289	Air release	Aerosol Spray	3	Toys, curtain, concrete, plastic etc.	Contains nano silver
280	Air release	Multi Purpose Spray	3	Applied on any surface	Contains nanosize silver/ titanium oxide particles
281	Air release	Odor Remover Powder	1	Chemical odors	No information accessible.
282	Air release/ Public sewer	Sun Screen for Car	1	Automotive sunscreen protectants	Contains TiO2
283	Air release/ Public sewer	Optics Cleaners	3	Cleaning (spray)	Nanofilms optical nanocoatings
284	Air release / Public sewer	Rain Repellent for Glass	4	Repelling rain, ice, snow.	Particles are nano-sized

	End of Life Category	Product	Number of similar products combined	Application	Where nano material is used
285	Air release / Public sewer	Sealing Spray for Stone & Concrete	3	Sealing the surface of walls	Utilizing the principles of nanotechnology
286	Air release / Public sewer	Ceramic /Glass Sealant	8	Sealing the surface	Glass and ceramic sealing consists of nano particles
287	Air release / Public sewer	Sealant Spray for Fabric and Mattress	6	Protecting polyester, mattress	No information accessible
288	Air release / Public sewer	Exterior/ Interior Paint	6	Applied on wall	Contains nano-particles
299	Air release / Public sewer	Spray for Ceramic Tiles	1	Cleaning ceramic /applied on tile	Inside of the product
290	Air release / Public sewer	Anti Fog Cleaning Agent	1	Cleaning lens	Nano-technology based anti-fogging coating & cleaning agent
291	Air release / Public sewer	Anti-Graffiti Coating	2	Resistant to corrosion, UV breakdown etc.	No information accessible
292	Other	Chemical Hazard Neutralization System	1	Can be use for acidic and caustic gases, chemical warfare agents.	Consist of nano-particles
293	Other	Plant Grow	1	Accelerate plant growth	Utilized from nanotechnology
294	Other	Soil Wetting Agent	1	Balanced water in soil	Light weight magnesium sheet with nanometer microstructures are using

CHAPTER 3

RECYCLING OF FIBER-REINFORCED COMPOSITES AND DIRECT STRUCTURAL COMPOSITE RECYCLING CONCEPT

3.1 ABSTRACT

Fiber-reinforced polymer composites are engineered materials commonly used for many structural applications because of the high strength-to-weight and stiffness-to-weight ratios. Although the service life of these materials in various applications is usually between 15 and 20 years, these often keep the physical properties beyond this time. Recycling composites using chemical, mechanical, and thermal processing is reviewed in this paper. In this review of carbon, aramide, and glass fiber composites, we provide, as of 2011, a complete view of each composite recycling technology, highlight the possible energy requirements, explain the product outputs of recycling, and discuss the quality (fiber strength) of recyclates and how each recyclate fiber could be used in the market for sustainable composite manufacturing. This paper also includes the new concept of "direct structural composite recycling" and the use of these products in the same or different applications as low-cost composite materials after small modifications.

3.2 INTRODUCTION

Composites are defined as a combination of two or more materials (matrix and reinforcement) to create a new engineered material. For composite applications, thermoset resins are the most commonly used matrix materials. Glass, carbon, and Kevlar fiber-reinforced composites are generally utilized for many applications, such as medical (medical bed frame and x-ray table supports), construction, electronics, agriculture (tank lids and structural roofs), recreation (bicycle and kayak), industrial appliances (assembly-line and robotic applications), aviation (fuselage, wing spars and avionics containers), automotive (body panel stiffeners for NASCAR, floorboards and firewall panels), furniture (tables and desks), and so forth (Composite Products, Inc &ACP Composite, 2011) .

Carbon fiber (CF) composites have gained considerable public attention through the marketing efforts of aircraft companies. A unique application of fiber-reinforced composites can be found in the 787 Dreamliner, a long-range, mid-size, twin-engine jet airline, recently developed by the Boeing Company. These composites will potentially extend to additional uses in the aviation industry and other industries. The 2006 world capacity of carbon fiber composites was about 25,000 metric tons per year and at that time was expected to grow to 35,000 metric tons per year (Davidson, 2006). A similar expectation is true for glass fiber composites. In some cases, there may be a shortage of both fiber and composite manufacturing to meet the new demands. However, if the fibers used in these composites are recycled or reused in the market, then this could extend the lifetime of fibers already utilized in the composite industry and prevent shortages for future applications (Composite Products Inc., 2011).

Every year thousands of tons of composites are manufactured worldwide for a variety of purposes. Although there are many successful applications of carbon and glass fiber composite materials, recycling is a major issue at the end-of-life (EOL) phase because of the conservation of fibers and composites for a longer period of time (Pimenta and Pinho, 2011; Pickering, 2006). The authors have identified some challenges for the reuse of composites:

- Composites are made of mixtures of different matrix and reinforcement materials: polymers, fibrous reinforcements (glass and carbon fiber), and fillers (e.g., particles, fire retardants, colorants, etc.).
- Composites are generally manufactured in combination with other materials, such as honeycombs, foam cores, metal and ceramic pieces, polymeric barrier films, and top coatings.
- Thermoset resins cannot be remolded again due to cross-linkages.
- Contamination can be a primary problem during the recycling process.
- Collecting, classifying, and separating the scrap materials can be challenging and costly operations.
- The lack of a continuous supply of recyclable composite materials occasionally limits the long-term investment.

- Recycling composites using conventional methods can create a waste management issue due to the formation of liquid waste (e.g., acids, bases, solvents and surfactants), gas and particulate emissions, and solid waste.
- Sometimes, it can be difficult to find qualified workers in the region for long-term sustainable employment.

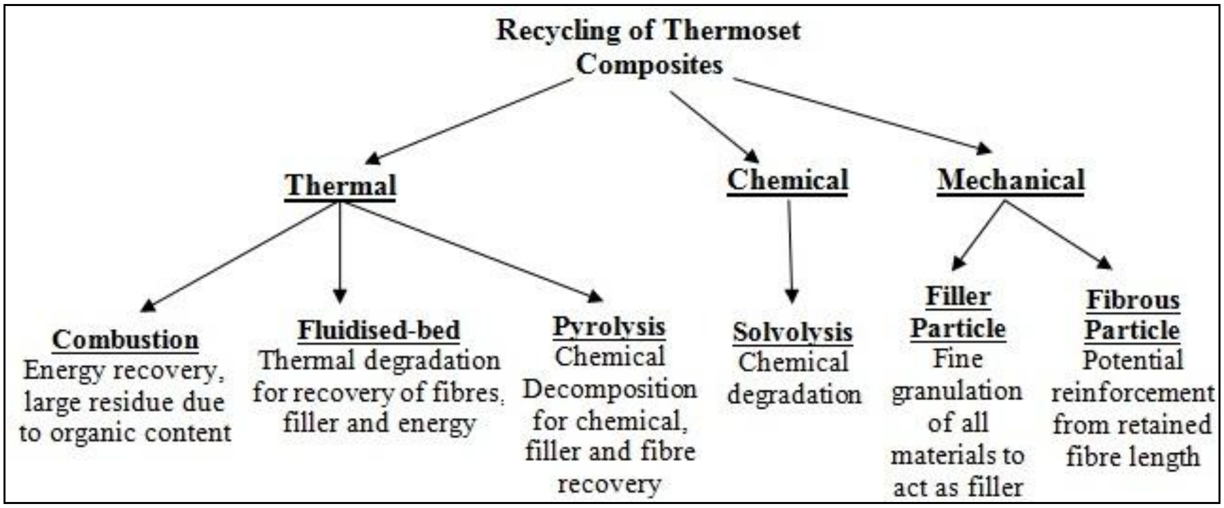
The noticeable lack of composite recyclability is critical because it is a potential impediment to the development and continued use of fibers and other composite materials in the market. This impediment is not shared by competing materials such as aluminum or steel. Generally, manufacturing carbon composites can create up to 40% scrap materials, which can end up in landfills or waste incineration (Recycled Carbon Fibre Ltd., 2011). Burning carbon composites can produce heat for various purposes, but it also needs control of emissions and ash deposition. Landfilling may be an option as a short-term solution; however, in this case, the loss of recoverable materials must be replaced with virgin or supporting materials. Recycling composites may thus provide lower material use with less landfill allocation, so the fiber composites will remain in use for a longer period of time in the same or different applications.

The following sections provide a detailed literature review of the current recycling technologies for the carbon and glass fiber composites and a new recycling approach: utilizing composites (direct reuse) with little modification for the same or different applications. This will also provide a low-energy input recycling system. Benefits of this direct-reuse recycling approach are discussed in detail. Market opportunities and a future outline for fiber-reinforced composites are sought for “as-is” recycled composites as well. In this study, the authors utilized several recycling companies’ web sites, annual reports, aviation magazines, and previously published articles (31 primary studies and four review documents).

Several review articles or magazines have been published in the area of composite recycling. Pickering (2006) analyzed recycling technologies for thermoset composite materials (six years ago). Pimenta and Pinho (2011) reviewed the recycling of just carbon fiber-reinforced plastic (CFRP) for structural applications, and the authors also looked at the market opportunities of these recycled products. Beaujon (2006) earlier analyzed the recycling of the carbon fibers from a composite bicycle. Gramann et al. (2008) studied the recyclability of materials that were mainly used for boat manufacturing. In this review of carbon, aramide, and glass fiber composites, we provide (as of 2011) a complete view of the each composite recycling technology, highlighting the possible energy requirements, product outputs of recycling, quality (fiber strength) of recyclates, and how each recyclate fiber could be used in the market for a sustainable composite manufacturing (Feraboli et al., 2012). This paper also includes the new concept of direct structural recycling of composites and the use in the same or different applications as low-cost composite materials after small modifications.

3.3 Composite Recycling Technology

A number of different recycling technologies have been developed and employed for fiber-reinforced composite materials because of the wider applications of glass fiber-reinforced plastics (GFRP) and carbon fiber-reinforced composites (CFRC) as well as long-term demands. These recycling methods are categorized as mechanical, chemical, and thermal, as depicted in Figure 3.1 (Palmer, 2009). In most composite recycling processes, a composite material is reduced to a smaller size and consists of mixtures of polymer, fiber, and filler. Generally, the smaller particles are in powder form, which contain a higher percentage of filler and polymer, while the coarser particles often contain fibrous structures where the products tend to have a high aspect ratio of fibers (Pickering, 2006).



Source: Palmer, 2009

Figure 3.1 Recycling of thermoset composites using thermal, chemical, and mechanical methods.

3.3.1 Mechanical Recycling

Mechanical recycling techniques start with cutting and grinding the scrap or retired composite materials into smaller pieces, and then sizing the different fragments. The smaller size increases the separation ability of the fibers and resin matrix (usually a thermoset resin) from the composite structures. These fine recycled products can be suitable raw materials for a wide variety of applications, including filler and reinforcement materials in new composite fabrication or other applications (Palmer, 2009). Even though the mechanical recycling methods were developed for the carbon fiber- and glass fiber-reinforced composites, the majority of the research has been conducted on glass fiber composites. Palmer (2009) used the single-fiber tensile testing method to compare the strengths of virgin and recycled fibers. For the recycling method, this author used mechanical recycling of injection molded products, which involved grinding and separation of the recycled products. More than 50 specimens were prepared and tested at 5 mm, 10 mm, and 15 mm gage lengths, for both virgin and recyclate fibers (Table 3.1). A significant decrease (between 18% and 30%) occurred in the mechanical properties of the recovered glass fibers compared to the virgin fibers.

TABLE 3.1 TENSILE TESTING OF VIRGIN AND RECYCLED GLASS FIBERS.

		Gage Length (mm)		
		5	**10**	**15**
Virgin Fiber	Tensile Strength (GPa)	2.08 ± 0.59	2.09 ± 0.56	2.1 ± 0.61
	Young's Modulus (GPa)	69.2 ± 13.5	70.35 ± 9.89	71.1 ± 13.5
Recycled Fiber	Tensile Strength (GPa)	1.72 ± 0.59	1.64 ± 0.48	1.48 ± 0.46
	Young's Modulus (GPa)	66.6 ± 14.1	64.9 ± 11.8	65.2 ± 10.3

Source: Palmer, 2009

An effective reuse of recyclable composite materials requires extensive size reduction and separation before ingredients can be used in new composites. Larger composite parts up to 5 m^2 can be cut or shredded, and then sent to other size reduction units, where these are then crushed and ground to be small enough for the new composite formation. Crushing and grinding requires energy input (Palmer, 2009).

In mechanical recycling processes, material size is reduced to less than 100 mm by slow-speed cutting and milling. Then, metal inserts are removed using magnetic fields. The major size-reduction stage consists of high-speed mills, such as a hammer mill, where the material is ground into a finer product (10-50 mm) by sharp hammers. Then, the recyclates are categorized into different sizes by using hydrocyclones and various sieves or shaking screens. Table 3.2 shows the consumption of energy needed for grinding processes for different types of composite materials. A total of 400 MJ is required to produce one kg of virgin carbon fiber, 200 MJ/kg of which comes from electricity and the remaining is for oil consumption (the yield of fiber from composite was not given, and so the energy per kg of composite is not established). As can be seen, the fiber-reinforced polymeric (FRP) sandwich structured composite consumes the highest energy (0.31 MJ/kg), while the glass mat-reinforced thermoplastic (GMRT) consumes the lowest energy (0.14 MJ/kg) during the grinding process (Åström, 2005).

TABLE 3.2 ENERGY CONSUMPTION OF GRINDING PROCESS FOR SOME COMPOSITE MATERIALS.

Material	Electrical Energy Consumption (MJ/kg material)
CFRP	0.27
FRP Sandwich	0.31
SMC	0.16
GMRT	0.14
PP/Flax	0.17

*CFRP (carbon fiber-reinforced plastic), FRP sandwich (fiber-reinforced polymeric sandwich), SMC (thermoset glass fiber composite sheet molding compound), GMRT (glass mat-reinforced thermoplastic) and PP/Flax (thermoplastic composite with polypropylene/flax as natural fiber). (Courtesy of the author).

Source: Åström, 2005

Recently, carbon fiber-reinforced plastic has gained attention as a light-weight material in the automotive industry. Conversely, the large energy consumption, difficulty in the recycling process, and high cost potentially limit the recycled use in this industry. Thus, the energy intensity of CFRP production needs to be reduced to the level of steel production and lower than other initial costs for mass-production in passenger cars. Suzuki and Takahashi (2005) found an effective way to reduce the energy intensity of CFRP to the level of recycling steel parts. This new technology involves reducing, reusing, and recycling CFRP. Also, choosing precise fiber fractions and matrix resin will likely reduce the energy intensity of CFRP production. The epoxy matrix is a commonly used thermosetting resin for aircraft and other high-tech products. Producing epoxy resin requires 76 MJ/kg, while polypropylene (PP) requires 24.4 MJ/kg. The energy intensity of carbon fiber part is 286 MJ/kg, which includes the raw material production, processing, and assembly (Suzuki and Takahashi, 2005). The authors also decided to use a 30% fiber volume fraction to produce the carbon fiber-reinforced thermoplastic (CFRTP) for car body parts. The composite manufacturing method used was matched die molding. The weight ratio between CF and PP was 0.462: 0.538, so the energy consumption of the CF was 132 MJ/kg, while that of PP was 13 MJ/kg. Energy intensity of the molding was about 10 MJ/kg. Thus, the total energy intensity of the CFRTP was 155 MJ/kg (Table 3.3) (Suzuki and Takahashi, 2005). CFRTP was used for the automotive body to provide high rigidity and light-weight automobile parts. Table 3.3 provides the energy consumed during manufacturing, which was based on the mass production of a car. Usually virgin steel is used for the manufacturing of automobiles due to the high-performance requirements, so the energy intensity is higher than other structural metals (33 MJ /kg). Overall, the energy of steel parts production is 49 MJ/kg, including 16 MJ/kg for processing and assembly.

TABLE 3.3 ENERGY INTENSITY (MJ/KG) OF VIRGIN AND RECYCLED MATERIALS.

	Steel	**Virgin CFRTS**	**Recycled CFRTS**	**Virgin CFRTP**	**Recycled CFRTP**
Assembly Molding	16	13	10	10	10
Steel or Matrix Resin Production	33	23	13	13	
Carbon Fiber Production		198		132	
Materials Recovery			10		5
Total Energy Intensity (MJ/kg)	**49**	**234**	**33**	**155**	**15**

Source: Suzuki and Takahashi, 2005

In order to produce composite carbon fiber-reinforced thermoset (CFRTS) for a car chassis, the authors used epoxy resin, which requires 76 MJ/kg energy. The CF and epoxy weight ratio was 0.692: 0.308, so the energy consumption of the CF and epoxy was 198 MJ/kg and 23 MJ/kg, respectively. The resin transfer molding (RTM) method used an energy intensity of 13 MJ/kg. Therefore, the energy intensity of the CFRTS was 234 MJ/kg (Table 3.3). On the other hand, recycled CFRTP required a total of 15 MJ/kg, which included melting and remolding processes without adding any resin. Recycling CFRTS required about 33 MJ/kg, in which 10 MJ/kg was for recovering CF (process requires transportation and washing), 10 MJ/kg for molding, and 13 MJ/kg for PP.

Takahashi et al. (2007), recycled carbon fibers from the carbon fiber-reinforced plastic to develop carbon fiber-reinforced thermoplastics. In order to recycle CFRP, the authors used both heat recovery and material recycling methods. This study included the evaluation of the energy intensity of the parts using CFRTP, carbon fiber-reinforced thermosetting resin, and recycled forms. CFRP was initially ground and dried at 80°C for eight hours. CFRTP pellets were made with the crushed CFRP and thermoplastics such as acrylonitrile-butadiene-styrene (ABS) and polypropylene using a two-axis pelletizing machine. Fiber volume fractions of the pellets provided by the authors were in the ranges of 7%, 15%, 24%, and 30%. In order to make specimens, the injection molding method was used for the ground CFRP (polyacrylonitrile [PAN]-based carbon fiber with epoxy resin). Several mechanical tests were performed on the samples, and results showed that 24% fiber volume fraction with the ABS thermosetting specimen provided higher flexural fiber strength (180 MPa) than other fraction volumes for both longitudinal and transverse loads. Recycled CF/PP longitudinal specimens with the 24% fiber volume fraction also provided higher flexural strength (100 MPa) than the other fractions and loading directions. Table 3.4 illustrates the influence of CFRP recycling on the energy savings for composite parts of automobiles. The numbers provided in Table 3.4 are approximate values from the authors' data (Takahashi et al., 2007). These findings and assumptions can be utilized for recycling aircraft and wind turbine composites, as well. As shown in Table 3.4, recycling CFRP decreases not only the composite waste (no numerical values given), but also the life-cycle energy consumption. The first row shows the material production, which consists of an energy requirement of the raw materials and resin production. The authors also indicated that CFRP (1), CFRP (2), and CFRP (3) materials require 17%, 21%, and 26%, respectively, less total energy compared to steel vehicles. The material recycling had a better life-cycle assessment (LCA) by reusing carbon fibers. Vehicle production consisted of the energy used during the processing and assembly of automobile parts. This row shows the total energy requirement during the usage of automobile and reflects the fuel efficiency, gasoline consumption, energy consumption of driving, and energy consumption of gasoline production. The last row of the Table 3.4 shows the end-of-life energy requirements for recycling (Takahashi et al., 2007).

TABLE 3.4 EFFECT OF CFRP RECYCLING ON ENERGY SAVINGS (MJ/KG) OF RECYCLING AUTOMOBILE PARTS.

Energy-Consuming Process	**Steel Vehicle**	**CFRP (1) CF/TS**	**CFRP (2) CF/TS + CF/TP**	**CFRP (3) (Recycled)**
Material Production	80	128	110	75
Vehicle Production	20	10	10	15
Use of Vehicle	370	255	255	260
End-of-life	10	5	5	5
Total Energy (MJ/kg)	**480**	**398**	**380**	**355**

CF/TS: Carbon fiber/thermosetting resin
CF/TP: Carbon fiber/thermoplastic resin

Source: Takahashi et al., 2007

Ogi et al. (2007) investigated the mechanical properties of a composite that contains acrylonitrile-butadiene-styrene resin incorporated with recycled carbon fiber-reinforced plastic parts (CFRP/ABS). CFRP parts produced by crushing CFRP waste (epoxy resin reinforced with carbon fiber) were utilized in this new material. CFRP pieces were produced through mixing, grinding, and injection molding procedures for the various blends of recycled and virgin fibers. Eight different composite specimens with various weight fractions and sizes were prepared to determine the mechanical properties. Table 3.5 gives the optimum combination of CFRP/ABS composites based on the strength values. Although Samples 6 and 7 provide the highest strengths with higher carbon fiber loadings, the shear stresses decreased due to less matrix in the composite.

TABLE 3.5 COMPOSITION OF CFRP/ABS COMPOSITE.

Name	CFRP	ABS	Volume Fraction (vf)	Strain	Strength (MPa)	Shear Strength (MPa)
Sample 2	0.1	0.9	0.041	0.0173	63.9	50.7
Sample 3	0.2	0.8	0.085	0.0124	73.8	43.6
Sample 4	0.3	0.7	0.132	0.0117	93.6	36.2
Sample 5	0.4	0.6	0.182	0.09	99.6	30.5
Sample 6	0.5	0.5	0.238	0.0075	100.8	24.7
Sample 7	0.6	0.4	0.298	0.0062	100.8	20.4

Source: Ogi et al., 2007

This study also shows that the tensile strength increases nonlinearly with increasing CFRP content, whereas the shear strengths of the new materials are considerably reduced from 50.7 MPa (Sample 2) to 20.4 MPa (Sample 7). In this work, a majority of the carbon fibers are individually separated and mixed well with the ABS resin system. It was concluded that some mechanical properties of the recycled composites were significantly higher after this process, which could be directly used in another application (Ogi et al., 2007).

Kouparitsas et al. (2002) studied the possibility of reusing short fibers obtained from the recycled thermoset composite to develop new composite materials. The authors initially recycled glass fibers from the glass polyester composites, and then separated the carbon and aramid fibers from the epoxy-based composites using the mechanical grinding method. After the grinding process, the authors specifically focused on fibers of the composites. To prepare new generations of composites, the recovered fibers were incorporated into the virgin matrix. Some of the specifications of the composites were as follows:

- Glass: recycled glass fibers incorporated with polypropylene at 40% w/w (vf: 12%) concentration.
- Carbon: recycled carbon fibers with ionomer at 20% w/w (vf: 9.6%) concentration.
- Aramide: recycled aramide fibers with ionomer at 15% w/w (vf: 9%) concentration.

The fiber length and residual resin content were characterized, and then the recycled fibers were incorporated into the virgin polymer matrix to manufacture the new composite. Mechanical testing results confirmed that the new composites produced using recycled fibers usually had similar mechanical properties as the virgin fiber composites. Some of the mechanical properties of the recycled and virgin composites are given below:

- The tensile strength of the new thermoplastic composites reinforced by recycled fibers is slightly greater (25 MPa) than the virgin fiber composites (24 MPa). Similar observations were also seen on the aramide fiber-reinforced composites. Compared to the ionomer/carbon composite, the new thermoplastic composite shows less strength than the virgin fiber composite (Table 3.6).
- The modulus of elasticity of the new generation of thermoplastic composites (polypropylene/glass) reinforced by recycled fiber is 1600 MPa, which is slightly lower

than virgin fiber composites (1680 MPa). The modulus of elasticity of ionomer/aramide is 270 MPa, which is also close to the virgin fiber-reinforced composite (300 MPa).

- The strain of the new generation thermoplastic composites reinforced by recycled fibers is 2.5%, while that of the virgin fiber composite is 3% (Kouparitsas et al., 2002).

TABLE 3.6 TENSILE STRENGTH OF FIBER-REINFORCED THERMOPLASTIC COMPOSITES.

	Tensile Strength (MPa)	
	Recycled	**Virgin**
PP/Glass	25	24
Ionomer/Aramide	14	12.5
Ionomer/Carbon	13	20.5

Source: Kouparitsas et al., 2002

Bernasconi et al. (2006) investigated the effects of mechanical recycling on the tensile strength of an injection molded polyamide 6, 6 reinforced glass fibers composite. In order to compare material properties, the tensile test was applied to both virgin and mechanically recycled material at different weight percentages. Mechanical recycling consisted of a series of steps: grinding the specimens and further injection molding the granules into specimens of the same type. In this step, four different sets of experiments were conducted using 0%, 25%, 50%, and 100% of reprocessed materials, which were obtained by in-plant recycling of the virgin materials (especially ground materials of tensile test specimens). The granules were mixed with new pellets and stirred well, and then the mixture was fed into an injection molding machine. Tensile test specimens of the short glass fiber-reinforced polyamide 6, 6 contained 35wt% of type E glass fibers (PA66 GF 35) of 10.5 µm average diameter. Temperatures of the mold and of the melting process were 70°C and 280°C, respectively, with an injection speed of 80 mm/s. The tensile test specimens were ground in a granulator of 2.2 kW power at 300 RPM, but the researchers did not report flow. Table 3.7 gives the elastic moduli and strengths of the different blends of virgin and reprocessed PA66 GF 35.

TABLE 3.7 ELASTIC MODULI AND STRENGTHS OF DIFFERENT BLENDS OF VIRGIN AND REPROCESSED PA66 GF35.

Material	Elastic Modulus (MPa)	Strength (MPa)	Strain (%)
Virgin	10840	187.4	2.87
25% Reground	10750	185.3	2.85
50% Reground	10730	180.5	3.00
100% Reground	10270	165.5	3.04

Source: Bernasconi et al., 2006

The tensile strengths of these composites were decreased, while the strain values were slightly increased as a function of recycled fibers in the composites. The main conclusion of this recycling process was that the recycled fibers were shortened and distributed randomly in the new composites, resulting in lower composite strength as compared to the longer virgin fibers. Thus, the applications for these recycled composites need to match a possible minimum strength for the same or different applications. The authors' micro-mechanical model also confirmed the test results with predicted values of the composites. As a result of this study, it was concluded that the model was very helpful in designing a methodology of the composite recycling process (Bernasconi et al., 2006).

3.3.2 Thermal Recycling

Several thermal recycling technologies have been developed and applied to fiber-reinforced composite materials. These are combustion, fluidized bed combustion, and pyrolysis. The thermal processes mainly require external heating to decompose the scrap composites into different products (e.g., solid, liquid, and gas). Every polymeric material has a calorific value, so the composite waste can also be converted into heat to produce electricity.

3.3.2.1 Combustion Process

Thermal recycling processes provide different degrees of energy and material recovery using heat to break the scrap composite, as can be seen in Figure 3.1(Pickering, 2006). Thermosetting polymers (e.g., the organic part of the composite) have a high calorific value, which can be burned to produce a source of energy, which in turn may be converted into mechanical energy or electricity.

Glass fiber-reinforced composites can be burned in a cement kiln where glass silica is added to the cement while the organic part provides a source of heat (Beaujon, 2006). This process is particularly important for inorganic, short fibers or particles that are very hard to recover from the resin part of composites. It also reduces the overall cost of cement production since heat is the major cost in the process. In addition to the cement applications, the recovered short silica fibers can be reused for new composite and other manufacturing purposes. The author claimed that the mechanical properties of these recycled short fibers were close to the same type of virgin composites, but no data were presented.

In another study, glass fiber and filler composites were burned at an elevated temperature to obtain the inorganic parts of the composites. Then, the inorganic parts of the composites were used in the sheet molding compound (SMC) process, which is a ready-to-mold fiber-reinforced polyester material primarily used in compression molding. According to Palmer (2009), the SMC has substantial non-organic components, such as fillers and glass fibers, so the resin is the only combustible organic material in the system with up to 35% of the total formulation weight. The classic SMC formulation provides 6.7 MJ/kg energy after burning in incineration. At 35wt% organic matter, the energy per kg organic is about 19 MJ/kg. Some of the mineral fillers (calcium carbonate) and fire retardants are decomposed at high temperatures and absorb some of the useful energy. Additionally, after the combustion process, a large amount of leftover residue (or ash) requires disposal and landfilling, which can potentially increase the recycling cost and other environmental concerns. This residue cannot be used as fillers in a new SMC or dough molding compound (DMC) materials because at higher temperatures, heat converts calcium carbonate into calcium oxide, which adversely affects the thickening process in virgin material production (Palmer, 2009).

3.3.2.2 Fluidized Bed Combustion Process

For more than a decade, a number of different studies have been performed to develop a fluidized bed combustion (FBC) process and recover high-grade glass and carbon fibers from scrap carbon and glass fiber-reinforced composites. The recovery of the reinforcing materials is found to be fairly high when compared to other similar processes used for the recovery of filler and resin ingredients. This method works at elevated temperatures (450–500°C) to thermally decompose the chopped fiber-reinforced composites in a silica sand bed that is thermally heated and fluidized by hot air. The organic part of the composite is volatilized by the hot air and then transported in the air stream with the silica particles before separating and collecting solid particulates (e.g., fillers, fibers, and sand particles). Note that the melting temperature of glass is usually between 1400°C and 1600°C, which is well above the burning temperature of carbon fibers and resins at ambient conditions. The volatilized resin component can be burned to produce heat and energy, while fillers and fibers can be reused in a new composite manufacturing for the same or different applications (Palmer, 2009).

A new fluidized bed combustion method was developed and used for the recycling of thermoset composites for various scrap composites (Pickering et al., 2000).

It was reported that this method provided a very useful product of fibers and a heat source for the recycling process. One of the main obstacles is that the size of the composites needs to be reduced prior to the treatment process conducted at 450°C and 1.3 m/s fluid velocity. After the burning process, 5 mm lengths of recycled fibers were collected using a rotating sieve separator, while smaller size fibers were collected with the filler materials at the end of the combustion system. Table 3.8 shows the required pre-processing details and fiber grades for various types before the fluidized bed combustion process.

TABLE 3.8 REQUIRED PRE-PROCESSING DETAILS AND FIBER GRADES FOR VARIOUS TYPES BEFORE FLUIDIZED BED COMBUSTION PROCESS.

Composite Feed	Single Molding Compound	Filament Wound Pipe	Sandwich Panel
Pre-Processes	Shredded	Hammer Milled	Hammer Milled
Size Range	< 6.7 mm	< 10 mm	< 10 mm

Source: Pickering et al., 2000

Using the FBC process, recyclate glass fibers undergo a 50% reduction in tensile strength, while still maintaining stiffness after the 450°C processing temperature. However, at a processing temperature of 650°C, the fibers lose about 90% of the mechanical strength, which may be because of additional changes in the fiber length and clustering effects of smaller fibers. Carbon fibers show only 20% reduction in the original stiffness after processing at 550°C. Surface analysis of the recycled carbon fibers also shows that surface oxidation of the carbon fibers is relatively low, indicating that recycled carbon fibers would have a good potential to bond the resin matrix when reused in a composite fabrication. The author also found that silane groups were mainly removed from the surface of the carbon fiber, so a silination step was applied for a better composite manufacturing. However, test results showed that after the silination process, no significant improvement was observed in terms of mechanical strength (Pickering et al., 2000).

A new study also showed that recycled glass and carbon fibers can serve as important sources of fiber in many high-tech manufacturing processes and offer several benefits, such as economic, environment, and health (Carberry, 2008). Making new carbon fibers from the recycling of old carbon fibers can save up to 70% of the cost with less than 5% of the electricity (Table 3.9). Thus, it can be concluded that recycling CFRP will be an economically and environmentally viable process.

TABLE 3.9 ESTIMATED VALUES FOR COST OF CARBON FIBERS.

Fiber Type	**Manufacturing Energy (MJ/kg)**	**Price ($/kg)**
Virgin Carbon Fiber	198–594	31–63
Recycled Carbon Fiber	10.8–36	17–25

Source: Carberry, 2008

Kennerly et al., 1998, and Pickering et al., 2000, defined a new fluidized bed combustion process to recycle glass fibers in scrap thermoset composites. Kennerly et al., 1998, focused on a processing scrap made out of polyester SMC. The scrap materials had a thickness of about 3 mm, and then were crushed and sieved to less than 25 mm size.

With the aim of glass fibers recovery, the authors applied 450°C to 600°C temperature to the scrap sheet molding compounds. The recovered fibers were washed in order to remove the loosely bound contaminates, which were up to 60% fillers by weight. Various levels of reclaimed fiber from the fluidized bed at 450°C replaced virgin fiber to make dough molding compound samples. This study reported that 50% of the virgin fiber could be replaced by the recovered fibers from the scrap. Increasing the replacement amount did not affect the flexural and tensile stiffness much while decreasing the tensile and flexural strengths, strain at peak load, and impact strength. The recovered glass fibers lost half of the strength compared to the virgin fibers. The authors claimed that the recovered fibers could still be used as a partial alternate to the virgin fibers in a DMC. Blending recycled and virgin fibers can be an option to adjust the physical and chemical properties of the new composites (Kennerley et al., 1998)

Jiang et al. (2007) used a soft ionization mass spectroscopy technique coupled with thermogravimetry (TG) analysis to examine the oxidative alteration of carbon fiber/epoxy resin composites. A comparison study was made on the decomposition of the epoxy in air and argon atmospheres, and it was found that the first step of decomposition in air was about the same as that of argon. Throughout the devolatilization process, the oxidative alteration then underwent a thermal alteration, resulting in the formation of a larger amount of volatile products including water, CO, CO_2, and other carbon- and hydrogen-associated gasses (Jiang et al., 2007).

Turner et al. (2011) studied the development of the new recycled carbon fiber molding compounds. The input process is one of the most critical steps in recovering the high value fibers from any recycling process. For example, prior to the fluidized bed combustion system, higher fiber lengths in the chopped composite could result in longer recycled carbon fibers, which in turn would increase the mechanical strength of the resultant composites. The same scenario would be true for other fibers in the composite system as well. The shorter fibers in the chopped composites will expectedly provide shorter recycled fibers from the FBC system and thus lower mechanical properties of the new composites.

The authors also investigated the granulating process for comminution (size reduction) of fibers from scrap prepreg. The six prepreg materials used in this study had diverse resin systems and fiber types. The main decisive factor in selection was the weave style (lightweight, large unit cell woven, heavy woven, unidirectional, ± 45 non-crimp fabric, and triaxial non-crimp fabric). Cutting width and speed were 300 mm and 150 rpm, which are considered to be a slow granulation process. Granulator screens were used for the following sizes: 6 mm, 8 mm, 15 mm, 20 mm, and 25 mm. The authors concluded that sieving twice may improve useable material fractions by reducing dust levels while removing excessively large segments and thus narrowing the fiber-length distribution. The 6 mm and 8 mm screens were found to be the most efficient. The authors also emphasized sieving the recycled fibers using a number of classification techniques, so that the value of the longer fibers could be higher (Turner et al., 2010). Although sieving can increase the overall cost, the economic value and marketability of the final products will be much higher.

3.3.2.3 Pyrolysis Process

The main objective of the pyrolysis process is to degrade the organic part of the composite by means of external heat into simpler molecules in an oxygen-deficit environment. The simpler molecules can be gas or liquid, depending on the pyrolysis process, while the remaining part will be the fibers and filler materials from the composites. The processing temperature is usually between 400°C and 1,000°C, depending on the types of composites and reinforcement materials (Meyer, 2009). This temperature is high enough to completely degrade even the carbon fibers. The produced liquid (tar and other heavy liquids) materials can be used as oil or other products. Gaseous products (e.g., CO_2, H_2, CH_4, and other hydrocarbons) have low calorific value, but still as an energy source can self-sustain the process.

When considering pyrolysis of polyester sheet molding compounds, the products produced in the temperature range of 400°C to 700°C have outstanding properties (Table 3.10). The pyrolysis gases have a low calorific value of about 14 MJ/Nm^3, which at a density of 0.75 kg/m^3 are about 19 MJ/kg gas. The liquid products contain approximately

66% aromatic compounds and about 25% oxygenated compounds (e.g., ketones, carboxylic acids, alkylbenzenes, and aryl naphthalenes) with calorific values of about 37 MJ/kg. This is similar to the calorific value of fuel oil (Pickering, 2006).

TABLE 3.10 PYROLYSIS PRODUCTS FROM SMC, EXPRESSED AS % (WEIGHT) OF SMC

Temperature	400°C	500°C	600°C	700°C
Gas Yield (%)	10.5	11.0	11.5	12.8
Liquid Yield (%)	14.5	14.2	14.9	13.7
Solid Yield (%)	75.2	74.9	73.9	72.6

Source: Pickering, 2006

Torres et al. (2000) used different temperatures (e.g., 300, 400, 500, 600, and 700°C) for pyrolysis of sheet molding compounds of fiber-glass and ortho-phthalic acid polyester in laboratory conditions. The authors also determined that at lower temperatures (e.g., 300°C), the pyrolysis yield and characteristics of the gases increased for the fiber-glass and ortho-phthalic acid polyester because at this temperature, the gases contain more CO and less CO_2gasses, which makes the gross calorific value (GCV) considerably high. Considering the GCV, the pyrolysis oil produced at 300°C (33.9 MJ/kg) shows a lower value than that produced at 400°C (36.7 MJ/kg). However, there are no significant GCV changes over the 400°C temperature range. From the present study, solid residues of 72–82 wt%, liquid yields of 9–13 wt%, and gas yields of 6–12 wt% were obtained. The authors concluded that 40% by weight of the pyrolysis liquid can be used to make a petroleum oil, since pyrolysis liquid has a higher gross calorific value (34–37 MJ/kg). The obtained gas fraction is also very rich in CO, CO_2, and other gases, with gross calorific values in the range of 13.9–16.4 MJ/m^3, which has a density of 0.75kg/m^3 and calorific value of about 19 MJ/kg. It can be used for energy to self sustain the pyrolysis process (Torres et al., 2000).

The Milled Carbon Group launched a new pyrolysis process for CFRP (The Recycled Carbon Fibre Ltd.) in a pilot plant. The company previously developed "the world's first commercial-scale continuous recycled carbon fiber operation." This company claims that they can recycle most forms of composite wastes, including dry fiber, pre-preg, laminates, and many others (Recycled Carbon Fibre Ltd., 2011).

Material Innovation Technology (MIT) is a carbon fiber reclamation company located in South Carolina. This company also does molding and manufacturing operations utilizing a custom–designed, large-scale, three-dimensional engineered pre-form process (3-DEP™) machine. The factory is 50,000 sq.ft., and has the capacity to process 3 to 5 million pounds of carbon fiber scrap yearly (MIT., 2010).

In order to obtain clean fibers from carbon fibers incorporated with an epoxy resin matrix, Lester et al. (2004) used microwave-heating experiments to accelerate the pyrolysis process. Microwave heating will volatilize the polymeric compounds and help produce clean fibers for possible reuse in different applications. The authors mentioned that recovered fibers were moderately clean but still had some small remnants on the surface topology (Lester et al., 2004).

Meyer et al. (2007) optimized the pyrolysis process for recycling the CFRP matrix. The recovered fiber exhibited higher mechanical properties and therefore should be considered for the production of new composites, but no data were presented. The new composite was said to meet the requirements of the automotive industry (Meyer et al., 2009).

3.3.3 Chemical Recycling

In the chemical recycling process, the solid composite is dissolved into different liquid products using solvents and then used as raw materials for different applications. The solid waste is first mechanically ground to increase the material surface area, so that the diffusion process can be higher (Gramann et al., 2008). The chemical recycling process generally consists of degrading the polymeric matrix materials of composites into basic chemical solutions that can be directly utilized as fuels for the manufacturing of polymers and composite materials. The chemical process usually dissolves the organic part of the composites, so the remaining part will be the reinforcing materials and filler particles. Since the chemical process is a more gentle process than the other processes (e.g., mechanical and thermal), recycled fiber length and uniformity tend to be higher; however, this process consumes chemicals, such as acids, bases, solvents, and washing liquids.

Generally, chemical recycling processes uses solvent dissolution, either with organic solvents (solvolysis) or water (hydrolysis). The solvolysis process aims at degrading the polyester-styrene part of the composite resin through the reaction of ester linkages with refluxing that takes place in a solvent at various reaction times and solvent concentrations. Other process parameters, such as temperature, agitation, pressure, and catalyst can be changed to increase the kinetics of the solvolysis process. On the other hand, hydrolysis is a chemical decomposition process in which the dissolution of organic substances take place by water (Palmer, 2009). This process may reduce the value of the final product.

Liu et al. (2004) recycled carbon fibers from carbon/epoxy composites using a chemical method (hydrolysis) in which nitric acid was the main solution in the process. The authors used permeation chromatography, gas chromatography, and mass spectrometry techniques to prove that the epoxy resin could be completely decomposed into low-molecular-weight compounds. The major components of the compounds include 2, 4-dinitrophenol and 2-nitro-4-carboxylphenol. The authors recovered the undamaged and clean recycled carbon fibers from this process. The tensile strength loss of the single recycled carbon fiber was only 1.1% obtained under the conditions of 90°C and 8 M nitric acid solution (fiber to nitric acid solution ratio of 4 g: 100 ml). However, the absolute strength values were not given. During the experiments, temperature, acid concentration, and various acid ratios were tested. This method was used to liquefy the organic material, and the remaining carbon fibers were utilized to reinforce the outside structure of rocket engines (Liu et al., 2004).

Hernanz et al. (2008) investigated the chemical recycling method (solvolysis) for carbon fiber-reinforced composites using alcohols as reactive-extraction media. In the presence of this solution, epoxy resin was degraded and carbon fibers were captured with 85–99% of the strength compared to virgin fibers. A number of solvents including methanol, ethanol, 1-propanol, and acetone were used as degrading solvents for the resin in small-batch and large semi-continuous-type reactors at temperatures ranges of 200°C to 450°C. The flow system (e.g., 1.1 to 2.5 kg-alcohol/kg-fiber/min) in the large-scale and alkali catalyst (e.g., NaOH, and KOH from 0.016 to 0.50M) greatly enhanced the degradation process. At this particular condition, 95% of resin was degraded in less than 15 minutes. SEM images also confirmed that the fibers were long and straight with very minimum damages after the recycling process (Hernanz et al., 2008).

Adherent Technologies, Inc. (ATI) (2004), a composite recycling company located in Albuquerque, New Mexico, has been recycling thermoset carbon fiber composites and reclaiming milled carbon fiber (MCF) and chopped carbon fiber (CCF) in a closed system at very high efficiency and low fiber degradation. The recycled fibers are high quality for resale to thermoplastic molding compounders. ATI uses a wet chemical breakdown process for composite matrix resins to recover fibers from the matrix. The company reported that the recycled carbon fibers have ten times higher economic value than the recovered oils from the matrix resins. The produced fibers are cleaner (more than 99%) and in much better condition than those found in pyrolysis processes. This process also generates short carbon fibers of variable length, from micrometer to about 5 cm. This process can be suitable for other fiber recycling as well. This company has been marketing their products to the electronics, transportation, aerospace, sporting goods, and chemical industries for some time (Adherent Technologies, Inc., 2004)

In order to recover the CF from CFRP, Nakagawa et al. (2009) used depolymerization of thermosets under regular pressure. The authors reported that the application of their method was useful to recycle glass fiber-reinforced plastic so they tried the same method for recycling carbon fiber-reinforced plastic. The authors emphasized that "recycled CFRP" could be used to prepare nonwoven fabrics made from recovered CF. The potassium phosphate (K_3PO_4) was employed as a catalyst with benzyl alcohol (BZA) as a solvent to depolymerize the cured epoxy resin (EP) and unsaturated polyester resin (UP). The mechanical properties of the CFRP and recycled CF are given in Table 3.11. As can be seen, the mechanical properties and elongation of CFRP were improved about 1.4 times and 1.1 times, respectively, while the elastic modulus stayed the same, when compared to the GFRP (Nakagawa et al., 2009).

TABLE 3.11 MECHANICAL PROPERTIES OF RECOVERED CARBON FIBER-REINFORCED PLASTIC.

	Recycled Carbon Fiber-Reinforced Plastic	**Mass Production of Virgin Glass Fiber-Reinforced Plastic**
Tensile Strength (MPa)	89.7	63.8
Tensile Modulus (GPa)	5.5	5.7
Tensile Elongation (%)	4.0	3.7

Source: Nakagawa et al., 2009

With the purpose of recovery of the carbon fiber, Hyde et al. (2006) employed a supercritical propanol liquid, which has been used to extract the epoxy resin from the surface of a carbon fiber composite material. The authors mentioned that the process is efficient under the 50 bar pressure at 450°C. Also, the recovered fibers have nearly the same strength (3900 MPa) (Table 3.12) compared to the virgin fibers (4090 MPa) of the composites. The fibers used in the composite manufacturing were obtained using the fluidized bed and microwave methods (Hyde et al., 2006)

TABLE 3.12 MECHANICAL PROPERTIES OF VIRGIN AND THREE CARBON FIBER RECOVERY PROCESSES.

Properties	**Virgin**	**Fluidized Bed**	**Microwave**	**scPrOH**
Tensile strength (MPa)	4090	3050	3260	3900
Weibull Shape Parameter	8.4	5.4	7.6	8.6
Tensile modulus (GPa)	242	243	210	230

Source: Hyde et al., 2006

Dang et al., (2005) investigated the chemical recycling approach for the glass fiber-reinforced epoxy resin initially cured with amine solution, which was then decomposed in a nitric acid solution during the recycling process. After the decomposition and extraction processes, both the resin, in the form of a solution, and glass fibers were collected and neutralized for further applications. In this process, menthanediamine-cured bisphenol F type (BPF/MDA) epoxy resin was decomposed in a nitric acid rich solution, and then the polymer- rich liquid was repolymerized to produce the resin with the original properties. The authors claimed that the flexural strength of the recycled resin was slightly higher than that of virgin resin. It was also concluded that this approach was mainly applicable for the BPF/DDM epoxy resin and potentially used for an amine-cured epoxy resin system. (Dang et al., 2005).

Pimenta and Pinho (2011) investigated the current status of carbon fiber-reinforced polymer recycling methods, focusing on the fiber recovery and re-manufacturing processes, including the commercialization and potential applications of the recycled products. In order to recover the clean fibers from the CFRP, three methods were utilized: pyrolysis, oxidation in the fluidized bed, and chemical recycling (Pimenta and Pinho, 2011).The authors claimed that the pyrolysis process is the only thermal process that has commercial-scale implementation. Some of the chemical methods are advantageous regarding the mechanical performance of the recycled carbon fibers (rCFs), whereas the fluidized bed process is principally attractive for the end-of-life composites and contaminated waste. Apart from the fluidized bed process, the mechanical process is less likely to be used because of the variations in the recycled fiber size, shape, and length. The major technical challenges in the waste preparation include recycling of EOL parts and quality control of the rCFs. Re-impregnating non-woven mats is an effective method for the mechanical performance of the composites. The strength of the recycled carbon fibers and the virgin carbon fibers is shown in Table 3.13. Recycled carbon fibers obtained with the pyrolysis and chemical method were about equal in strength as the virgin fibers; however, the recycled carbon fibers from the fluidized bed process show less strength than virgin carbon fibers.

TABLE 3.13 STRENGTH OF RECYCLED CARBON FIBERS AND THE VIRGIN PRECURSOR.

	Strength (GPa)	
	Virgin Carbon Fiber	**Recycled Carbon Fiber**
Pyrolysis	3.6	3.7
Fluidized Bed	4.8	3.2
Chemical	5.2	5.2

Source: Pimenta and Pinho, 2010

When put into composites, the mechanical properties of the virgin fiber were slightly higher than the recycled fiber. The authors also reported that the pyrolysis process provided a better elastic modulus than the fluidized bed and chemical processes; in contrast, the last two provided higher strength and interfacial shear strength than the pyrolysis process. Surface contamination, fiber lengths, and mechanical properties are important parameters in terms of marketability (Pimenta and Pinho, 2011); (Szpieg et al., 2012).

3.4 Comparisons of Composite Recycling Technologies

Recycling thermoset composites is a critical subject of interest by industries, including the aircraft, automobile, shipping, construction, and wind energy industries. As is known, once thermosets are shaped and cross-linked (or cured), these materials cannot be remolded or melted again, which makes the recycling process even more difficult. If a thermoset polymer is used as matrix material in a composite, then recycling becomes more complicated due to the multi-phase nature of the composites. Tables 3.14, 3.15, and 3.16 compare the recycling technologies of various composites presently utilized by industry.

Table 3.14 shows preprocessing and possible energy requirements of composite recycling methodologies. As can be seen, most of the recycling studies were conducted in a laboratory environment and not at the industrial level. From Table 3.14, it is clear that most studies have not conducted the necessary energy analyses. The grinding step is in the 0.1–0.5 MJ/kg composite range. The whole recovery process from only two studies was in the 10–40 MJ/kg composite range, but data are very limited. This clearly indicates that the recycling of composites is in an early stage and will require further study.

TABLE 3.14 PREPROCESS AND POSSIBLE ENERGY REQUIREMENTS OF THE COMPOSITE RECYCLING METHODS.

Reference	**Recycling Method**	**Pre-Process**	**Energy Requirements (MJ/kg)**
Palmer, 2009	Mechanical recycling	Size reduction, cut, and shred	Unreported

Reference	Recycling Method	Pre-Process	Energy Requirements (MJ/kg)
Åström, 2005	Mechanical recycling	Hammer mill used for size reduction to about 0.1 x 0.1 m.	Energy consumption of grinding process CFRP = 0.27[1]; FRP-sandwich = 0.31[1]; SMC = 0.16[1]; GMRT = 0.14[1]; PP/Flax = 0.17[1]
Takahashi et al., 2007; Suzuki and Takahashi, 2005.	Heat recovery material recycling	Crushing	Required energy for material recovery 5 MJ/kg-CFRTP; 10 MJ/kg-CFRTS
Ogi et al., 2007	Mechanical (grinding)	Sizing may be required	Unreported
Kouparitsas et al., 2002	Mechanical (grinding)	Unreported	Unreported
Bernasconi et al., 2006	Mechanical (grinding)	Unreported	Grinding, washing, and drying are energy required processes
AdherentTechnologies, Inc., 2011	Wet chemical breakdown	Sizing may be required	Unreported
Nakagawa et al., 2009	De-polymerization	Unreported	Unreported
Hernanz et al., 2008	Solvolysis	Unreported	Energy of activation 95,591 J/ mol resin
Hyde et al., 2006	Solvolysis	Unreported	Heating is energy required process
Liu et al., 2004	Solvolysis	Unreported	Heating required for decomposition
Pickering et al., 2000	Fluidized-bed combustion	Comminuting	Unreported
Kennerly et al., 1998	Fluidized bed combustion	Crushing and sieving	Crushing, sieving, washing, drying, and heating are energy required processes
Turner et al., 2011	Fluidized bed combustion	Sizing may be required	Sieving ≈ 0.125 MJ/kg; Granulating ≈ 0.5 MJ/kg
Palmer, 2009	Combustion process	Sizing may be required	Unreported
Pimenta and Pinho, 2011	Pyrolysis, fluidized bed, chemical	Sizing may be required	Recycled carbon fiber manufacturing 10.8–36 MJ/kg
Pickering, 2006	Pyrolysis	Sizing may be required	400–700°F heat applied
Torres et al., 2000	Pyrolysis	Sizing may be required	300–700°F heat applied

[1] Electrical energy consumption for grinding process

Table 3.15 shows the composite recycling methods with the output of various products and byproducts. The output material can be used for different applications based on various properties, such as fiber length, modulus and strength, fuel value, and physical form, as shown in Table 3.15. Also, from this Table, it can be concluded that the most frequent output of recycling is recovered fiber, followed by energy (three cases), and to a lesser extent filler/resin and also liquid/gas products.

TABLE 3.15 COMPOSITE RECYCLING METHODS WITH THE OUTPUT OF THE RECYCLED COMPOSITES.

Reference	Recycling Material	Recycling Method	Output
Palmer, 2009	Single molding compound	Mechanical recycling	Mixture of resin, filler particles, and reinforcing fibers
Åström, 2005	Polymer composite material	Mechanical recycling	Powder, fiber, etc.
Takahashi et al., 2007; Suzuki and Takahashi, 2005	CFRP	Heat recovery material recycling	Carbon fiber
Ogi et al., 2007	CFRP	Mechanical (grinding)	CFRP pieces and carbon fiber
Kouparitsas et al., 2002	Thermoset composite	Mechanical (grinding)	Glass fiber, carbon fiber, and aramide fiber
Bernasconi et al., 2006	Reinforced glass fiber composite	Mechanical (grinding)	Glass fiber
Adherent Technologies, Inc., 2011	Thermoset carbon fiber composite	Wet chemical breakdown	Milled carbon fiber and chopped carbon fiber
Nakagawa et al., 2009	CFRP	Depolymerization	Carbon fiber
Hernanz et al., 2008	CFRC	Solvolysis	Carbon fiber
Hyde et al., 2006	Carbon fiber composite	Solvolysis	Carbon fiber
Liu et al., 2004	Carbon epoxy composite	Solvolysis	Carbon fiber
Pickering et al., 2000	Thermoset composite	Fluidized-bed combustion	Recovered carbon fibers, particulate materials, and heat
Kennerly et al., 1998	Scrap from polyester SMC	Fluidized bed combustion	Glass fiber

Reference	Recycling Material	Recycling Method	Output
Turner et al., 2011	Scrap prepreg	Fluidized bed combustion	Carbon fiber
Palmer, 2009	Glass fiber composite	Combustion process	Energy
Pimenta and Pinho, 2011	CFRP	Pyrolysis, fluidized bed, chemical	Carbon fiber
Pickering, 2006	SMC	Pyrolysis	Energy, gaseous, and liquid product ; liquid materials can be used as oil; gaseous products have low calorific value
Torres et al., 2000	SMC	Pyrolysis	Gaseous and liquid product

Table 3.16 provides a comparison of current recycling technologies based on the strength values of recyclates. Among the current recycling methodologies, the chemical recycling (see yellow column) technique offers the highest tensile strength values of fibers that can be used to produce high-strength new composites (generally 98% strength of virgin fibers). The mechanical recycling technology (blue column) provides the second-highest-strength fibers (about 75% strength of virgin fibers) and composites. The thermal recycling (gray column) methodologies (fluidized bed, combustion, and pyrolysis) yield fibers that have 50–75% less tensile strength compared to the virgin fibers (Dragon Plate, 2012 ; Barbero, 2010).

TABLE 3.16 FIBER STRENGTH OF RECYCLED COMPOSITE ASSOCIATED WITH RECYCLING METHODS.

Recyclers	Recycling Material	Recycling Method	Fiber or Composite Strength	Control or Virgin Strength Values
Adherent Technologies, Inc., 2011	Thermoset carbon fiber composite	Wet chemical breakdown	Recyclate fiber retaining 95+% virgin fiber 3325 MPa [1]	3500 MPa[1]
Nakagawa et al., 2009	CFRP	De-polymerization	Carbon fiber 89.7 MPa	Mass production of glass fiber 63.8 MPa

Recyclers	Recycling Material	Recycling Method	Fiber or Composite Strength	Control or Virgin Strength Values
Hernanz et al., 2008	CFRC	Solvolysis	85–99% of strength of virgin fibers, straight and long fibers 2975–3465 MPa[1]	3500 MPa[1]
Hyde et al., 2006	Carbon fiber composite	Solvolysis	3900 MPa	4090 MPa
Liu et al., 2004	Carbon epoxy composite	Solvolysis	Single-fiber tension strength loss of 1.1% of recycled carbon fiber 3461.5 MPa	3500 MPa[1]
Palmer, 2009	SMC	Mechanical recycling	1130–2310 MPa	1490–2670 MPa
Åström, 2005	Polymer composite material	Mechanical recycling	Unreported	Unreported
Takahashi et al., 2007; Suzuki and Takahashi, 2005	CFRP	Heat recovery material recycling	CF/PP L-24% ≈ 100 MPa CF/ABS L-24% ≈ 180 MPa	CF/PP L-24%; based on JIS expected flexural strength of 120 MPa; CF/ABS (almost same as virgin composite)
Ogi et al., 2007	CFRP	Mechanical (grinding)	Composite product (CFRP/ABS) 100.8 MPa	Unreported
Kouparitsas et al., 2002	Thermoset composite	Mechanical (grinding)	PP/Glass 25 MPa; ionomer/aramide 14 MPa; ionomer/carbon 13 Mpa	PP/glass 24 MPa; ionomer/aramide 12.5 MPa, ionomer/carbon 20.5 Mpa
Bernasconi et al., 2006	Reinforced glass fiber composite	Mechanical (grinding)	25% reground glass shows max strength of 185.3 MPa	187.4 MPa
Pickering et al., 2000	Thermoset composite	Fluidized bed combustion	Half of virgin fiber 1750 MPa[1]	3500 MPa[1]
Kennerly et al., 1998	Scrap from Polyester SMC	Fluidized bed combustion	Strength reduced to half of virgin glass fiber ≈1750 MPa	3500 MPa[2]
Turner et al., 2011	Scrap prepreg	Fluidized bed combustion	Strength reduced to around 50–75% of virgin fiber strength 1750–2625 MPa[1]	3500 MPa[1]
Palmer T., 2009	Glass fiber composite	Combustion process	Unreported	Unreported
Pimenta and Pinho, 2011	Carbon fiber-reinforced polymer	Pyrolysis, fluidized bed, chemical	Pyrolysis ≈ 3700 MPa; fluidized bed ≈ 3200 MPa; chemical ≈ 5200 MPa	Pyrolysis ≈ 3600 MPa; fluidized bed ≈ 4800 MPa; chemical ≈ 5200 MPa
Pickering, 2006	SMC	Pyrolysis	Unreported	Unreported

Recyclers	**Recycling Material**	**Recycling Method**	**Fiber or Composite Strength**	**Control or Virgin Strength Values**
Torres, A. et al., 2000	SMC	Pyrolysis	Unreported	Unreported

[1] Approximate virgin carbon fiber strength: 3500 MPa
[2] Approximate glass fiber strength (E glass): 3500 MPa

3.5 Direct Structural Recycling of Composites

In all current composite recycling technologies, energy is needed for grinding and separation. Often only the fiber is recovered for a very low-mass yield. Thus, it is desirable to explore how to use more of the composite mass and at a higher material value.

A new approach called "**direct structural composite recycling**" is mainly based on product and scrap composite materials reused without any chemical or structural changes. The major concept here is that large composite products can be cut into small-size structural pieces that can be directly used in small composite products. The requirement is that the end-of-life composite is larger (length and width) and has the right thickness for the intended product applications. Some composite scrap will be produced since the size match of retired and new products is not the same. These scraps from resizing would be candidates for the other recycling method described in this article. The economic concept is that having the smaller size structures with high-strength composite properties (which is normally expensive) but which are now essentially free would stimulate "as-is" recycling by manufacturers or designers of new products. These newly available small composite structures would thus solve the EOL issue of large composite product manufacturers (aircraft, ships, cars) and make available a beneficial raw material for new smaller-size products.

The new approach, shown in Figure 3.2, utilizes scrap or EOL composites coming from various sources, such as wind turbines, boats, aircraft, and automobiles. In this case, it may be easier to cut down the larger recycled composites into small pieces and reuse these. Based on the target product, the scrap material and retired products will be collected, sorted, cut, and reprocessed. Sanding and painting may be the final step of the process. An economic analysis should be investigated for the entire supply chain of the direct structural composite recycling approach. Keep in mind that the recycled and scrap composites must have enough mechanical strength for the present approach.

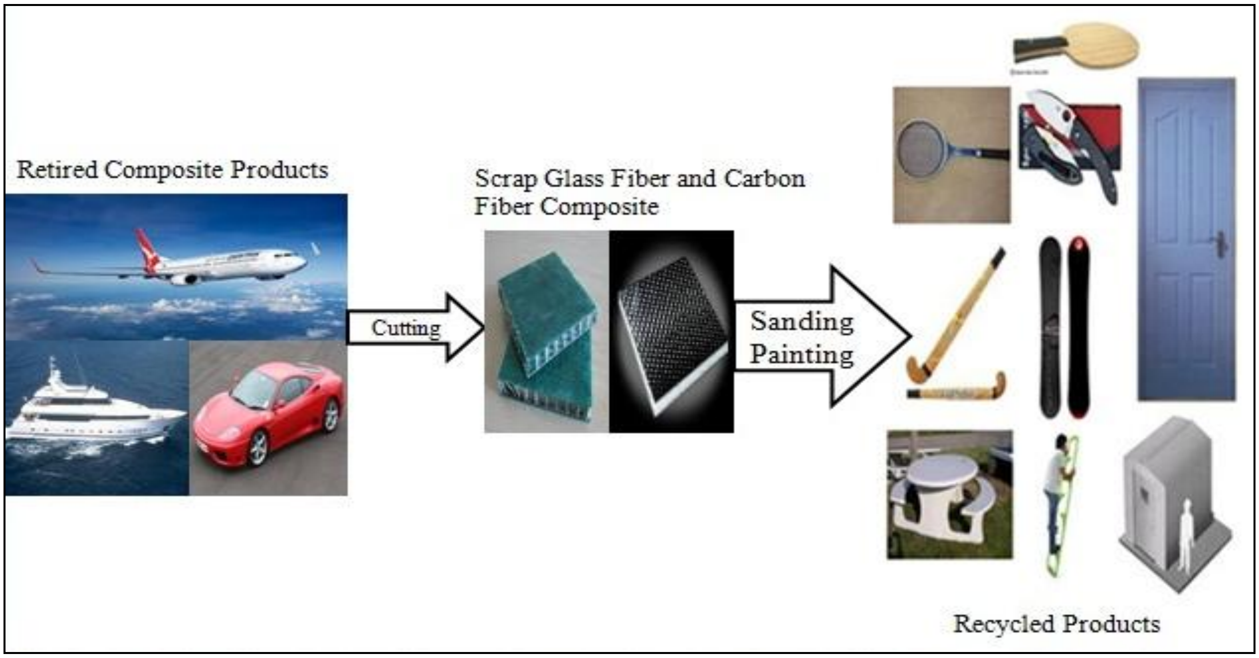


Figure 3.2. Recycling of fiber-reinforced composite materials for use in different applications after little modification.

3.6 Conclusions

Composites are high-strength and light-weight products, and have been used for hundreds of different applications. However, these composites are costly materials. Thus, composite recycling is an essential process in order to sustain such a big investment in the composite field. Within a life cycle analysis framework, exploring the end-of-service-life of composite products offers several benefits, including environment, education, health, social, and economic benefits. The current literature suggests that fiber recovery is the primary goal of most studies in this field. Across the three major types of composite recycling technologies, chemical recycling provides the highest-strength fibers (relative to virgin equivalents). The next provider of high-strength fibers is mechanical recycling, followed by thermal technologies. It is clear that the energy and economic analyses of composite recycling needs additional attention. As with most recycle-reuse industries, the next phase is development of enhanced recycling infrastructure, with cost-sharing such as consumer fees with new products, state support for industry location and jobs, and expanded markets for recycled materials. The mechanisms for supporting this enhanced recycle-reuse infrastructure are unclear at this time.

Direct structural composite recycling may be an important novel approach for the composite and recycling industries. This study has shown that the composite products appear to have better value if they are recycled or reused as composite structures rather than composite constituents (e.g., fiber, filler, reinforcement, etc.). This also requires fewer natural resources, and less energy and labor to produce new high-technology products for various industries, such as construction, furniture, automobile and other transportation, electronic, etc. Finally, the direct structural recycling of composite products will open up new possibilities for the sustainability of composites and fibers.

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LIST OF ACRONYMS

ABS	Acrylonitrile-butadiene-styrene
ATI	Adherent Technologies, Inc.
BPF/MDA	Menthanediamine-cured bisphenol F type (BPF/MDA) epoxy resin
BZA	Benzyl alcohol
CCF	Chopped carbon fiber

CF	Carbon fiber
CFRC	Carbon fiber-reinforced composite
CFRP	Carbon fiber-reinforced plastic
CFRTP	Carbon fiber-reinforced thermoplastic
CFRTS	Carbon fiber-reinforced thermoset
CF/PP	Carbon fiber/polypropylene)
CFRP/ABS	Carbon fiber-reinforced plastic/acrylonitrile-butadiene-styrene
CFRC	Carbon fiber-reinforced composite
DMC	Dough molding compound
EOL	End of life
EP	Epoxy resin
FRP	Fiber-reinforced polymeric
FBC	Fluidized bed combustion
GCV	Gross calorific value
GFRP	Glass fiber-reinforced plastic
GMRT	Glass mat-reinforced thermoplastic
K_3PO_4	Potassium phosphate
LCA	Life-cycle assessment
MIT	Material Innovation Technology
MCF	Milled carbon fiber
NASCAR	National Association for Stock Car Auto Racing
PP/Flax	Thermoplastic composite with natural fiber as polypropylene/flax
PP	Polypropylene
PAN	Polyacrylonitrile
PA66 GF 35 fibers	Glass fiber-reinforced polyamide 6,6 contained 35wt% of type E glass
RCF	Recycled carbon fiber
RTM	Resin transfer molding
scPrOH	Supercritical propanol
SEM	Scanning electron microscope
SMC	Sheet molding compound
TG	Thermogravimetry
3-DEP™	Three-dimensional engineered pre-form process
UP	Unsaturated polyester resin

CHAPTER 4

RECYCLING OF AIRCRAFT – STATE-OF-THE-ART 2011

4.1 ABSTRACT

Recently, the end-of-service life of aging aircraft and related parts has become a key subject in recycling industries worldwide. Over the next 20 years, approximately 12,000 aircraft currently utilized for different purposes will be at their end of service. Thus, reclaiming retired aircraft in an environmentally responsible while retaining some of their value becomes a significant need. Recycling aircraft components and using them in different applications will reduce the consumption of natural resources as well as landfill allocations. Compared to the production of virgin material, recycling aircraft will also reduce air, water, and soil contaminations, as well as energy demand. In the present study, we have investigated the environmental benefits of recycling and reusing aircraft in the same or similar applications as for low-energy input materials. During the aircraft recycling, most of the aircraft components can be recycled and reused after reasonable modifications and investments.

4.2 INTRODUCTION

"Wastes from one industrial process can serve as the raw materials for another, thereby reducing the impact of industry on the environment" (Frosch and Gallopoulos,1989). This statement is one of the major motivations for the authors to focus on recycling aircraft and related components. Recycling aircraft is a series of activities: collecting recyclable materials and devices from aircraft that would otherwise be considered waste, and sorting and processing those useful materials into raw materials for future aircraft and other industrial applications. Hundreds of recyclable materials are available in aging aircraft, and this number continually increases, based on economic and technological developments in the field. At their end of life (EOL), aircraft are often placed in aircraft graveyards /parking places where they sit and degrade as the result of environmental influences, such as UV light, moisture, and oxygen/ozone. In most cases, the useful materials from aircraft are high-tech and should be valued for future production and materials conservation. The following section will focus on aircraft recycling companies, aircraft recycling methodologies, and related references. Environmental benefits associated with aircraft recycling and rising market perception of regained products will be reviewed.

Generally, aircraft are composed of a number of different materials and devices, including long and short carbon and glass fiber composites, wires, aluminum, titanium and steel alloys, foam, textiles and carpet, landing gear, fluids, electronic devices, engines, and other parts. Sometimes the complexity of materials and devices in aircraft (e.g., military, business jet, and civilian) can reduce the recyclability rate; therefore, during the initial design, manufacturers should consider the EOL of aircraft.

4.3 RECENT PROGRESS IN AIRCRAFT RECYCLING

Currently a number of aerospace alloys, including aluminum and magnesium based alloys, as well as nickel, cobalt, and titanium based alloys, have been produced and used for aircraft manufacturing. Aluminum alloys are mainly copper, zinc, manganese, silicon, and magnesium. The two main classifications of aluminum based alloys are cast and wrought, both of which are subdivided into heat-treatable and non-heat-treatable categories. Approximately, 80% of aluminum alloys are produced by the wrought process in the form of sheets and foils that are higher in strength and lower in density, which are desired by the aircraft industry. Among the major aluminum alloys commonly used in aircraft and other aerospace applications (helicopters and spacecraft)—7075, 6061, 6063, 2024, and 5052—the 7075 aluminum alloy is most preferred by the aircraft industry. Its composition includes 5.1%–6.1% zinc, 2.1%–2.9% magnesium, 1.2%–2.0% copper, and less than 0.5% of silicon, iron, manganese, titanium, chromium, and other trace metals. These alloys are extensively employed in aircraft fuselages and other engineering structures and compounds in which light weight and corrosion resistant materials are highly required.

Additionally, specially designed alloys make it possible for the aircraft industry to produce high-strength products for jet engines and airframes where high temperature, pressure, and vibration are essential during design and manufacturing. Also, stainless steel, nickel, copper, titanium, and their alloys are the major components of aircraft alloys employed for engine blocks, providing high strength and the ability to perform at particularly high temperatures and pressure (Davis, 1993).

Bombardier became the first original equipment manufacturer to emphasize aircraft dismantling operations and, in turn, obtained a dismantling certification from the Aircraft Fleet Recycling Association (AFRA) in 2010. The company successfully dismantled a CRJ100/200 regional jet, which was recognized by the AFRA as one of the best practices in the field. In August 2010, Bombardier and Magellan Aircraft Services of Charlotte, North Carolina, disassembled 10 CRJ100/200 regional jets for refurbishing and remarketing useable components for different aircraft companies. They recovered 1,500 reusable parts, including 300 line-replaceable units per jet (Bombardier, 2011).

Carbon Fiber Remanufacturing (CFR), a company established in 1997 in Whitewater Kansas, specializes in the recycling of carbon fiber of composites. This company generally recycles scrap carbon fibers obtained from the manufacturing process and reuses about 30% of them in further manufacturing processes to make new composites. CFR utilizes detangling, cutting, and hammer milling processes to remanufacture carbon fiber scraps for different product applications. The recycled carbon fibers are used as secondary raw materials without any mechanical property losses, so the remanufactured carbon fibers have nearly 100% of the virgin carbon fibers. These can be cut into specified lengths (0.6 cm–7.5 cm) and integrated into non-woven rolled cloth products and compounds for the preferred specifications. They can be added into fiber-reinforced plastics and polymers to make composites, and also blended with glass and Kevlar fibers in order to develop new products. Recycled carbon fibers can be used in structural, insulation (thermal and acoustic), and filtration (air and liquid) applications. CFR provides many recycled materials to local and national aircraft industries, as well as appliances, agriculture, construction, automotive, waste water filtration, trucks, textiles, military equipment, outdoor products, power generation, and sporting goods (CFR, 2011).

Recent studies show that the AFRA's series of best management practice guides have become the industry standard for dismantling and recycling aircraft (AMD, 2011). Since 2008, 16 companies have been accredited by AFRA worldwide, 10 of which are located in the U.S. and the remaining in Europe (AFRA, 2012). Since these companies were certified by AFRA, they have experienced in how to dismantle and disassemble aircraft efficiently. They offer a reliable source of high-quality aftermarket airframe spares to global customers, primarily including avionics, electronics, engines, rotables, landing gear, interior decorations, and other flight control parts (AFRA, 2012). Thus, AFRA is the major accreditation process and provides the aircraft and recycling industries with all necessary procedures and tools in order to maximize environmental efficiency and economic profit during aircraft disassembly. This increases the value of the recyclable aircraft in their EOL by developing new technologies and approaches that utilize higher-valued materials and devices from aircraft and other closely related industries.

AFRA and Boeing also intend to reduce the amount of aircraft manufacturing waste transferred to the landfill by 25% by 2012. AFRA is the global organization dedicated to environmentally responsible management of airplanes during their EOL service and also to the persistent practice of continual life-cycle improvement. According to the AFRA, the quality of recycled composite materials needs to be improved, and new applications and markets for inside and outside the aviation sector need to be defined. Recycling also makes excellent business sense, because the market desires are satisfied at lower costs (AMD, 2011).

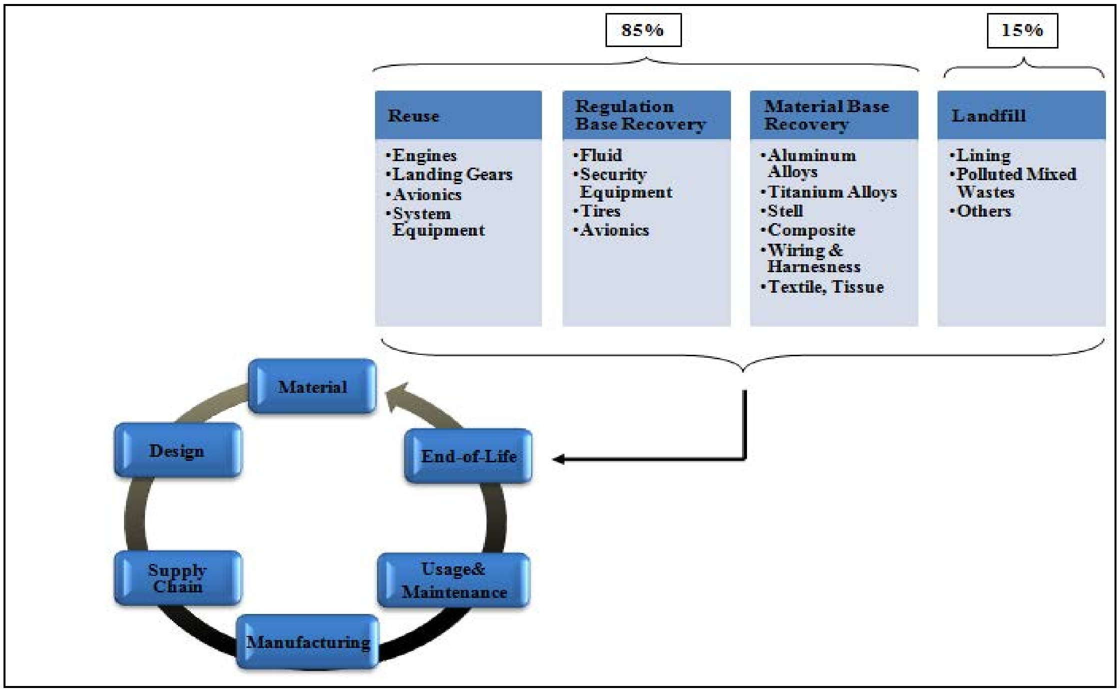
Processing for the advanced management of EOL for aircraft (PAMELA) is a programme for aircraft dismantling that is supported by the European Commission's "LIFE" initiative. This dismantling project mainly focuses on subjects, including management, recycling, and reduction of landfills. In this project, the Airbus Company dismantled a 24-year-old airplane (A300B4) into four categories: structure, cockpit/cabin /cargo, systems, and power plant. The main idea behind the project was to increase the amount and quality of materials from retired aircraft. Purity was not the main issue in this project, but the quantity and amount of recovered materials (e.g., mostly non-ferrous materials) were considered major advantageous. Unlike current processes, dismantling was more efficient and recovered up to 70%–80% of the scrap by weight for reuse.

According to Airbus, recovered scrap metals are considerably pure, so that the recovered aluminium alloys and other parts can be reused directly in the aerospace industry.

In addition to economic returns, recycling has environmental benefits, as well. For example, aluminium manufacturing is an energy-intensive process due to the electrolysis step (or Bayer process). However, when aluminium is directly recovered and reused, it reduces the initial energy by 90% (Airbus, 2008), which in turn also reduces raw material consumption. The dismantling process consists mainly of three steps defined by PAMELA. The first step is decommissioning, which includes cleaning, draining of tanks, and various safety procedures. The second step is disassembling, which consists of equipment and parts removal from the body of the aircraft. The third step is the final draining of the systems, removal of hazardous materials, and deconstruction of the aircraft. According to Airbus, some of the components can be reused if the conditions of the parts are still in good shape, such as engines and engine parts, the auxiliary power unit, landing gear, avionics, system equipment, and movable parts and devices. Many other good-quality materials and devices can be directly recycled and reused as provided below:

- Some components, such as fluids (fuel, oil, and hydraulic fluid), security and safety equipment, batteries, avionics, and tires (requiring regulatory recycling).
- Aluminum, titanium, and nickel alloys; hot-rolled and corrosion-resistant steel alloys; wiring; harnesses; thermoplastics; foams; textiles; carpeting; and papers/tissues with special recycling techniques.

- Cabin and cargo lining, wastes, and various other parts that are not recovered and usually go to landfills and aircraft graveyards.
- All composite parts of the aircraft, including the fuselage and interior parts could be potentially utilized in other industries.
- The entire aircraft used for demonstrations and exhibitions in shows and museums for raising public attention to aviation.



Source: Adapted from PAMELA-Life Project Led by Airbus (Airbus France S.A.S., 2008).

Figure 4.1 Life cycle of aircraft and reverse supply chain for future use as efficient and low-cost materials

Figure 4.1 shows the aircraft life cycle as well as a reverse supply chain of an airplane. It was reported that the initial weight of an average airplane is 106 tons, and after three steps in the dismantling process, about 85% of the airplane materials could be recovered and the remaining 15% put in landfills (Airbus, 2008). The 85% of the recycled parts are either used, as is, in the same field, or modified for other applications. Further studies are needed for the unrecoverable materials and parts of the aircraft. It was recommended that the remaining 15% of the components and materials such as interiors could be used in other aircraft (Kingsley-Jones, 2008; Tarmac Aerosave, 2011; Reals, 2011). Airbus reported that approximately €250–€300 could be spent per ton of dangerous aircraft parts during storage, such as with asbestos and hexavalent chromium (chromium VI) of the aircraft skin. Lately, Airbus has been persistently working on this subject to further decrease the high costs of the landfill allocations (Kingsley-Jones, 2008; Tarmac Aerosave, 2011)

P3 Aviation is the United Kingdom-based supplier of rotating components (e.g., engines, actuators, turbines, generators, and alternators), aiming to take advantage of the growing market for dismantling and recycling aircraft. This company supervises the removal process from aircraft during the deregistering, dismantling, and selling of parts at their highest values. The company has already dismantled seven aircraft in 2010, and successfully turned aircraft scraps and cabin parts into cash. According to the company, the interior part of the aircraft generally goes to the landfill, but they have sold entire interiors of Boeing 737–400 airplanes. The company also sells diverse aircraft parts for use as office furniture and for decoration purposes. The fuselage has been utilized for desk partitions, flaps and stabilizers for boardroom tables, and engine inlet cowls as reception desks in bars and restaurants (Reals, 2011).

With the aim of recycling plastics and composite materials from aircraft, Allred and Salas (2005) investigated a low-temperature catalytic tertiary recycling process. They claim that the catalytic conversion process could transform all types of plastics (e.g., rubber, thermosets, and thermoplastics) into valuable hydrocarbon products and fuels. Catalytic conversion, a closed-loop process without access to the environment, is nonpolluting because of the rapid conversion times. Other experiments on the utilization of used plastic blast media, hazardous waste streams, and composite scraps and parts involve a low-temperature catalytic conversion process. It was stated that using this conversion process for recycled plastics and other hydrocarbon-associated materials could reduce hazardous substances by a factor of five. Inorganic parts, such as heavy metals and other oxides, could be remelted to eliminate their toxicity and used in aircraft. Imide, polyester, epoxy, and other engineered thermoplastics and composite matrices could be converted into low-molecular-weight hydrocarbons to produce valuable fibers for reuse in the fabrication of additional composite materials for aircraft and other industries. Economic analysis illustrates that a recycling plant based on this method will have a return on investment of one to two years. An interrelated technology illustrated a significant amount (100 ton/day) of recycled tires use, confirming that there is a high possibility of implementation with a large-scale tertiary recycling of plastics, and composites (Allred and Salas,2011).

It is reported that the recycling of cured composite materials used for aircraft manufacturing is a difficult process because of the complexity of the composite structures (Asmatulu et al., 2013).These materials are produced using thermosetting epoxy matrices that form an intimate connection with the surfaces of fibers, metals, and coatings. Recent techniques developed to recycle thermoset composites were recently studied (Asmatulu et al., 2013). Because of the structural concerns of these recycled fibers, the materials may not regain the original values of reinforcing fibers in order to be directly used in the fuselage structures of aircraft.

The Boeing and Alenia Aeronautica companies founded Italy's first aircraft composite recycling facility of materials for future manufacturing. This facility processes an average of 1,102 tons of composite scrap yearly and creates roughly 75 jobs in the regional economy. Boeing also cooperated with Milled Carbon Limited to establish a pilot industrial plant for processing cured and uncured composite parts on a continuous basis in order to extract high-quality carbon fibers. The recycled material is likely to be utilized for non-critical structures of aircraft, such as galleys, interior linings, seat parts, and tools that produce stronger and lighter-weight materials in the same industry (Boeing, 2008).

Most of the wires used in aircraft are conductive metals (e.g., copper, silver. and aluminum) of various sizes and shapes, covered by plastic insulators. Recently, fiber optic cables have been used in aircraft manufacturing, as well. Among the wires and cables, copper is the most commonly used for electrical wiring in aircraft. It was reported that the Boeing Dream Liner 787 has about 60 miles of cables, while Boeing 777 has about 100 miles of cables (Boeing, 2008). Once the metal wires are properly removed from aircraft, recycling is easier. Larger-scale wires are shredded and then granulated into smaller particles, so that separators (e.g., gravity, electrical, and optical) can remove the metals from the plastic parts. For instance, an eddy-current separator is one of the frequently utilized electrical separators in which granulated copper wires are fed into the separator to remove copper particles from the plastic particles. Both of these materials can be used in aircraft after the melting and reprocessing steps. For very-thin copper wires, the recycling process becomes quite complex. In this case, burning the plastic part of the wires can be the main option for metal recovery, and the heat produced during the burning process can be used in the same industry as an energy source. Depending on the size and complexity of the wires and recycling methods, the recovery rate of wires and cables can vary from 50% to 90%, or even more (Anonymous 1).

Yi et al. (2008) offered an algorithm on the disassembly strategy of mechanical parts in aircraft that relies on the disassembly wave concept. This method is relatively simple and also proficient to search and develop. Furthermore, the method offers an optimal and selectable disassembly sequence of mechanical components with lower numbers of computing and processing steps. This is considered to be a very significant process for maintaining, recycling, and discarding aircraft parts. The authors conducted a study of wave propagation for the selectable disassembly analysis. They claimed that the wave propagation method provides an optimal sequence to disassemble the selected components with the wave that propagates from the selected component to a set of boundary components. The authors also discussed geometric algorithms for both single-dependent and multiple-dependent components. The major drawback of the study was the identification of an optimal sequence used for the selected items with the minimal component removals and examining a division of components from the assembly (Yi et al., 2008).

4.4 MARKETABILITY OF RECYCLED AIRCRAFT MATERIALS

The major components that can be recycled from aircraft include wires, electronics, aluminum and other alloys, stainless steel, many other organic and inorganic compounds and carbon and glass fibers (Carberry, 2011). Recycling offers economic and environmental benefits because of less energy consumption, labor, and emissions (solid, liquid, and air). Figure 4.2 shows aluminum sheets that were recycled from aircraft and used for aluminum tile products. The energy consumption of the recycling process is 5% of that required for first-generation aluminum production. Service scrap and manufacturing scrap can be recycled and reused to reduce the consumption of natural resources and mining operations worldwide (Coveringsetc, 2011). Another direct application of the recycled product is in iPad cases, which are made of a solid block of recycled aircraft aluminum (Anonymous 2).

Source: http://www.coveringsetc.com

Figure 4.2 Photographs showing aluminum sheets recycled from an aircraft (left) and reused as tiles (right)

Carbon fibers recycled from a military aircraft (F18) were aligned and integrated into a compression molding unit to make new composites. Materials Innovation Technologies (MIT), located in Fletcher, North Carolina, fabricated automotive parts from recycled fibers using chopping, mixing, and molding processes. Chopped composite parts from the F18 were delivered to both Milled Carbon and Adherent Companies. These fine composites were successfully injection molded to produce different compounds for testing and evaluation. Test results confirmed that the mechanical strength of the injection molded parts were closely matching with the shelf virgin carbon fiber filled compounds. Figure 4.3 shows a Corvette C6 fender well component molded from recycled F18carbon fiber. As can be seen, the Corvette component (Figure 4.3a), produced from recycled carbon fiber (Figure 4.3b), is about 20% lighter than the fiberglass components, even without any engineering processes. The stiffness of the new composites was also significantly enhanced by adding the recycled fibers (George and

Carberry, 2007).The recycled and remolded products are currently being utilized in the car.

Lastly, an aircraft engine can comprise up to 80% of the total value of the aircraft, depending on the applications for which it will be used. The remaining part of the plane can be sold as spares for approximately $350,000. Engines (Figure 4.3c) are the first items to be taken out of an aircraft at the recycling facility. They are first checked and then investigated for further use in another airplane. Most of these high-tech materials (e.g., nickel, cobalt, chromium alloys) with very high mechanical strength and high temperature and corrosion resistance are placed in aircraft engines, so the recycling value of these materials are considerably higher than other aircraft parts (Cacciottolo,2011).

Source: George and Carberry, 2007

Figure 4.3 Corvette C6 fender well component (a) molded from recycled F18 carbon fiber (b) removed aircraft engine (c) at recycling facility

4.5 ENVIRONMENTAL IMPACTS OF AIRCRAFT RECYCLING

By reducing the amount of energy used by the aircraft industry, recycling reduces greenhouse gas (GHG) emissions and minimizes global climate change. Additional benefits of recycling would be a reduction in emissions from incinerators, and less polluted materials to the landfills, which may eventually eliminate air, water and soil contaminations. Table 4.1 shows the energy savings of different recycled aircraft materials. For example, aluminum and copper recycling from scrap has 95% and 85% less energy requirements, respectively (Lund, 2000). Utilizing secondary raw materials reduces the use of natural resources. The third column of Table 4.1 shows the energy savings of recycling metals and related materials. Compared to the concentrating that occurs in mineral processing facilities and the smelting that goes on in metallurgical plants, recycling needs only about 10% of the total investment, increases employment, facilitates the sustainment of a practical manufacturing base, and eradicates landfill waste (Das et al.,2011; BMRA,2011).

TABLE 4.1 ENERGY SAVINGS OF RECYCLED MATERIALS IN COMPARISON TO VIRGIN PRODUCTION, AND PERCENTAGE OF NEW METALS PRODUCED BY USING RECOVERED METALS

Recycled Materials	**Separation Techniques**	**Energy Savings (%)**	**New Metals Produced by Using Recovered Metals (%)**
Steel	Hand-sorting, Magnetic	62–74	42
Aluminum	Electrostatic, Hand-sorting, Eddy current	95	39
Copper	Electrostatic, Eddy current, Hand-sorting	85	32
Lead	Gravity, Hand-sorting	60–65	74
Zinc	Gravity, Hand-sorting, Flotation	60	20
Paper	Flotation, Hand-sorting	64	N/A
Plastics	Electrostatic, Eddy current, Hand-sorting	80	N/A

Source: Lund, 2000 and BMRA, 2011

Damgaard et al., (2009), assessed greenhouse gas emissions associated with the recycling of metals from post-consumer waste in the frame of waste management. A material recovery facility (MRF) was used for the sorting the recovered metal. According to the authors, GHG emissions are derived from three sources: indirect upstream emissions, direct activities at the MRF, and indirect downstream processes needed in reprocessing the metal scrap. Energy savings results from the avoided production of virgin metal. The global warming factor (GWF) of the upstream activities and the MRF as GHG emissions were 12.8–52.6 kg CO_2/ton recovered aluminum and 400–1020 kg CO_2/ton recovered steel. Reprocessing is associated with a large savings as the result of avoided virgin production of aluminum and steel. The authors defined a net downstream savings of 5,040–19,340 kg CO_2/ton of the treated aluminum and 560–2360 kg CO_2/ton of the treated steel. The authors concluded that recovery of the scrap metal mainly relies on the technology and method chosen during the recycling processes, which make the comparison a little more difficult. Energy usage during the recovery and the avoidance of energy used in primary production are also important issue (Damgaard et al., 2009).

Other studies have confirmed that regained fibers from recycling serve as feasible replacements for new fibers within many high-end industrial manufacturing processes, and also offer a noteworthy savings of money and carbon dioxide emissions. Recycled carbon fiber can be made at about 70% of the cost with 98% less energy than manufacturing virgin chopped fiber. It is estimated that commercial jet manufacturing will create up to two million pounds of carbon fiber scrap in 2014. Recycling and substituting carbon fiber for virgin fiber in manufacturing and applications would save enough electricity to power 175,000 typical homes in a year (Carberry, 2011; Coveringsetc, 2011)

TABLE 4.2 EVALUATION OF VIRGIN AND RECYCLED CARBON FIBER

	Cost to Manufacture	
	Materials (US $/lb)	**Energy (kWH/lb)**
Virgin Carbon Fiber	15–30	25–75
Recycled Carbon Fiber	8–12	1.3–4.5

Source: Carberry, 2008

According to Jim Stike, CEO of the recycling firm Materials Innovation Technologies, using recycled carbon fiber not only avoids the waste of virgin carbon fiber being sent to landfills after its first use, but also produces new parts because carbon can maintain a significant portion of the virgin properties even after a second reclamation. As well, the recycling process for the fibers reduces energy costs. Based on Boeing's estimates, carbon fiber can be recycled at approximately 70 percent of the cost to produce virgin fiber (Table 4.2) ($8/lb–$12/lb vs. $15/lb–$30/lb), using about 5 percent of the electricity required (1.3–4.5 kWH/lb vs. 25–75 kWH/lb). In addition, MIT is willing to capitalize on the potential high quality of the recycled chopped carbon fiber to efficiently create intermediate-modulus materials that can be used for virgin aerospace and industrial-grade products (Wood, 2011). Table 4.3 shows the environmental impact (environmental load unit) of virgin carbon fibers on energy consumption during the manufacturing process (Åström, 2005). In order to produce 1 kg of virgin carbon fiber, 400 MJ of total electrical energy (equivalent to oil) is required. Using more energy in the conventional virgin processes will indirectly increase the gas emissions because the energy is mainly coming from the fossil fuels, so recycling makes a huge impact on the environment (Åström, 2005).

TABLE 4.3 ENVIRONMENTAL IMPACT ASSOCIATED WITH PRODUCTION OF ONE KG OF CARBON FIBER

Energy Source	**MJ/kg**	**CO_2 (kg)**	**NO_X (kg)**	**SO_X (kg)**	**Environmental Impact (ELU)**
Electricity	200	26.8	0.06	0.1398	7.8
Oil	200	39.8	0.0363	0.0302	12
Total	**400**	**66.6**	**0.0936**	**0.17**	**19.8**

Source: Åström, 2005

Aircraft recycling activities in the world promote development of communities and social interactions between communities. Other social impacts consist mainly of an increased lifespan made possible through a cleaner environment; safer working conditions for employees and employers; increased citizen interest in seeking employment or volunteer work in recycling; and improved scientific, cultural, and other activities nationally and internationally. Recently, social as well as educational impacts of recycling have been gaining much attention globally.

4.6 LIMITATION AND FUTURE RESEARCH

Recycling provides a number of different benefits to the environment and economy. For use as interior materials of aircraft, recycling competes with the option of disposal (AMD, 2011). Although the AFRA emphasizes this issue, several companies are already reusing aircraft interior parts for furniture, decoration, and art components. One of the dismantling programs is based on the A300-B4 airplane, which contains 4%

composites, 4% titanium, 12% steel, 77% aluminum, and 3% other materials, so this specific model contains a high ratio of aluminum (77%), while later models contain a high ratio of composites. Thus, a better composite recycling process for higher composite-containing airplanes should be investigated for each airplane. The most-efficient recycling methods need to be defined for composite materials of various size and shapes, and marketability should be sought in detail (Hayes, 2006).

For more than four decades, thousands of obsolete aircraft have been sitting in the Southwest desert; however, the demand for recycled aluminum is still increasing. The abandoned aircraft have great potential as a source of valuable metals and fibers for several industrial applications. Nevertheless, cost-effective recycling of aircraft alloys is difficult due to the fact that they characteristically have quite high levels of alloying elements, such as zinc (7xxx series) and copper (2xxx series), and low levels of minor elements, in order to optimize fracture toughness and other mechanical and corrosion properties. Changing the structure and types of aircraft materials makes the recycling process more complex and challenging (Das et al., 2007).

According to Das, 2009, feasible aluminum recovery is 90% or greater for the old aircraft. Aluminum alloys contain high amounts of zinc and copper, which makes the recycling process more complicated than the lesser-alloyed aluminum and other alloys used in other applications. Specific recycling trials are needed to make aircraft recycling more economic and efficient (Das, 2009). From a market point of view, the recycling of glass fiber is not practical because of its low cost (< $1/lb) and a sufficient supply of virgin glass fiber available to the market. However, recycled carbon fibers have a higher demand in the market because of the lower cost and similar physical properties compared to the virgin fibers, so it is economically more feasible for many companies (Patel, 2010). Lastly, the design stage is very important due to the cost of raw materials and recyclability of products. Designing a product in a reliable and recyclable way should be investigated in detail for each aircraft produced.

4.7 CONCLUSION

Recycling aircraft parts offers numerous environmental benefits, including reduction of water, soil, and air pollution, as well as landfills. Some of the materials (composites and alloys) in aircraft are costly to produce, so regaining these kinds of materials at a reasonable price is an environmentally responsible approach that is of great interest to recycling and aircraft industries. Aluminum is a high-demand material for most industries, so recovering this material with less effort has gained the considerable interest of many industries. Recycling of a material requires less energy than that of producing virgin material and also reduces gas emissions (e.g., CO_2, CO, NOx, and SO_2) and other emissions. A direct recycling (or as-is recycling) methodology can be used for some aircraft components, such as engines and electronics. Also, using aircraft components for furniture and decoration requires less energy because it necessitates only some basic processes such as cutting, reshaping, sanding, and painting, in order for them to be turned into sophisticated furniture for many consumers.

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DEFINITIONS/ABBREVIATIONS

AFRA	Aircraft Fleet Recycling Association
CFR	Carbon Fiber Remanufacturing
EOL	End of Life
GHG	Greenhouse Gas
GWF	Global Warming Factor
MIT	Materials Innovation Technologies
MRF	Material Recovery Facility

CHAPTER 5

EVALUATION OF RECYCLING EFFORTS OF AIRCRAFT COMPANIES IN WICHITA

5.1 ABSTRACT

The number of manufactured aircraft has been continuously increasing worldwide because of the high demand for airline transportation. During manufacturing, many advanced materials and devices are used to build various sizes and shapes of aircraft. However, most of these materials and devices require considerable energy and labor to produce, so reusing these at any life stage of the aircraft offers many economic and environmental benefits, and is considered lucrative and environmentally responsible. Several recyclable materials—composites, metals and alloys, wires, wood, paper, plastics, electronics, and avionics—emerge as waste streams during the manufacturing of aircraft. Many aircraft companies have been recycling these materials to remanufacture aircraft parts or other products for more sustainable production. In the present study, we evaluated the recycling efforts of local aircraft companies in Wichita, Kansas. These efforts were considered in terms of recycling efficiency/rate and environmental benefits. These included cradle-to-gate (CTG) life-cycle inventory analysis of the materials, carbon dioxide emissions, virgin material replacement with recycled materials, and natural resources usage. Our findings show that significant contributions to sustainability

as well as environmental and health benefits in the region can be made from recycling in aircraft manufacturing plants.

5.2 INTRODUCTION

Aircraft are composed of a number of different materials and devices, including carbon, glass and Kevlar fiber composites, aluminum, titanium and steel alloys, wires/cables, textiles and carpets, foams, landing gears, fluids, electronic and avionic devices, engines, and several other useful parts (Asmatulu, 2013(a)). Aerospace alloys—such as aluminum-, magnesium-, cobalt-, nickel-, and titanium-based alloys—have also been produced and employed in the manufacturing of aircraft. Among the aluminum alloys used for aircraft, helicopters, and spacecraft applications, series 2000, 5000, 6000, and 7000 are the most desired by the aircraft industry for use in fuselages and other engineering structures of aircraft (Davis, 1993). These diverse materials become scrap or excess during the production of aircraft and thus represent potential input to the recycling/reuse industry.

The Carbon Fiber Remanufacturing Company was established in 1997 in Whitewater, Kansas, in order to recycle scrap carbon fibers obtained from the process of manufacturing composites. About 30% of these recycled products are used in further manufacturing processes to make new composites. The remanufactured carbon fibers have nearly 100% of the properties of virgin carbon (Asmatulu et al., 2013(b)) fibers and can be used in structural, insulation (thermal and acoustic), and filtration (air and liquid) applications (Remanufacturing.org, 2013)

Typically, recycled wires from aircraft manufacturing are shredded and granulated into smaller sizes, and then gravity, electrical, and/or optical separators remove the metal parts from the plastics. Based on the size, shape, and complexity of the wires and recycling methods, the recovery rate of wires and cables can be in the range of 50% to 90% (Boeing, 2008).

The UK-based aviation company, P3 Aviation, supplies various parts, such as generators, whole engines, turbines, alternators, and actuators, and takes advantage of the growing market for dismantling and recycling aircraft as well as aircraft manufacturing waste materials. This company carefully removes the rotating aircraft parts throughout the dismantling procedure and sells these to customers. In 2010, P3 Aviation had already dismantled seven aircraft and successfully turned aircraft scraps and cabin parts into cash (Reals, 2011). Many other aircraft parts—carpets, textiles, paper, landing gears, fluids, foams, electronic and avionic devices, and others—can be efficiently recycled and used in the same or different industrial applications. In the present study, we evaluated the recycling efforts of five local aircraft manufacturing companies in Wichita, Kansas.

5.3 METHODOLOGY

Advanced materials used for aircraft manufacturing are expensive and may require high energy input to produce. Reclaiming these advanced materials provides several benefits: reducing the natural resource usage, lowering landfill allocations and environmental impact (air, soil, and water), increasing job opportunities, improving the nation's energy efficiency, and stimulating the recycled product market. Recently, environmental and economic returns have made advanced materials recycling more attractive, and many companies have already recognized this as the future of aircraft manufacturing.

In this study, we focused on the recycling efforts during aircraft manufacturing based on recycling efficiency and environmental benefits. In order to evaluate these criteria, we catalogued cradle-to-gate (CTG) life-cycle inventory analysis of the materials, carbon dioxide emissions, virgin material replacement with recycled material, and natural resources usage. CTG analysis is an assessment of a *partial* product life cycle from resource extraction (*cradle*) to the factory gate (i.e., before it is transported to the consumer).The data for potentially recyclable materials were collected from five major aircraft companies located in Wichita, Kansas and represent the year 2009.

Table 5.1 provides a 2009 profile of the annual generation of recyclable materials from five different aircraft companies (Bombardier, Spirit Aero Systems Holdings, Inc., Hawker Beechcraft, Cessna, and Boeing). In that year, 302, 309, and 754 aircraft were produced by Bombardier (McCoy, 2010) , Hawker Beechcraft (HawkerBeechcraft, 2010), and Cessna (Cessna, 2010), respectively. In that same year, 1,029 aircraft parts (mainly fuselages) were also manufactured by Spirit AeroSystems, Inc. (Spirit AeroSystems Holdings Inc., 2010), and 14 planes were modified at Boeing. According to

McMillin (2010), in the first quarter of 2009, Wichita manufacturers delivered 459 airplanes (McMillin, 2010). Overall in 2009, the number of aircraft and number of major components produced by the five aircraft companies were approximately 1,780 and 1,029, correspondingly. Thus, the city of Wichita is often referred to as the "Air Capital of the World" (Platzer, 2009). Also, a large quantity of aircraft equipment and parts were produced in Wichita and then delivered to other major aircraft companies worldwide.

TABLE 5.1 TOTAL POTENTIAL AND ACTUAL RECYCLABLE MATERIALS FROM AIRCRAFT MANUFACTURING FACILITIES IN WICHITA IN 2009 (1,765 PLANES AND 1,029 MAJOR COMPONENTS).

Recyclable Aircraft Material	**Potential Recyclable Materials (kg/yr)**	**Actual Recycled Materials (kg/yr)**
Aluminum	11,142,988	2,228,598
Construction/demolition debris (concrete, asphalt wood, sand, gravel, soil)	6,204,730	1,240,946
Food waste and trash	2,800,486	560,097
Solvents	2,775,529	555,106
Caustic spent aqueous solutions	2,125,260	425,052
Ferrous metal (steel)	1,528,682	305,736
Paper	1,132,948	226,590
Wood	1,128,048	225,609
Cardboard	976,654	195,331
Oil (all types, from sources like engines, hydraulics, etc.)	754,017	150,803
Nonferrous metal (not aluminum)	741,790	148,358
Blast media group (contaminated chips, corn starch media, steel media, tape, etc. as used in paint removal)	351,806	70,361
Paint-contaminated solids	331,349	66,270
Composites	216,817	43,363
Plastic bottles from employees	102,648	20,530
Plastics from all industrial operations (shipment packaging, blow molding, containers, etc.)	99,337	19,867
Paints (outdated)	28,236	5,647
Electronics	15,429	3,086

Recyclable Aircraft Material	**Potential Recyclable Materials (kg/yr)**	**Actual Recycled Materials (kg/yr)**
Batteries (all types, such as dry cell, NiCad, lead acid, etc.)	15,120	3,024
Florescent lamps	9,466	1,893
Coated wire	8,954	1,791
Tires	5,445	1,089
Tyvek suits	3,402	680
Toner cartridges	3,261	652
Tin	2,431	486
Gloves	907	181
Kevlar	482	97
Coolant	—	—
TOTAL	**32,506,224**	**6,501,245**

In 2009, aircraft production in Wichita generated about 33 million kilograms of recyclable advanced materials, indicating that the production of aircraft creates several recyclable components and scraps for future sustainable aircraft or other product manufacturing. Based on Table5.1, aluminum is the material with the highest availability for recycling. Construction and demolition debris are the second highest material, followed by food waste and trash, which represents leftovers from the company's staff during the aircraft manufacturing process. Various solvents are also produced and recycled during aircraft manufacturing. The remaining components have a smaller recyclable volume/quantity than the first four items.

5.4 RESULTS AND DISCUSSION

5.4.1 Cradle-to-Gate Inventory Analysis

Due to the potential benefit of aircraft material recycling and the scarcity of associated data, cradle-to-gate life-cycle inventory analysis is critical. This analysis is essentially a life-cycle map covering all inputs (e.g., materials, energy, and fuels) and outputs (e.g., products, co-products, wastes, and emissions) gathered throughout the entire material or product lifetime. The data are then converted into resources consumed as well as emissions to air, water, and soil. Table 5.2 gives the results of the CTG energy requirements of aircraft materials. The first column shows the type of recyclable aircraft materials, while the second column shows how much energy is used during the CTG life cycle of these new materials, beginning with fossil resources or the mining operation of ores all the way through the factory gate. The third column shows the approximate energy used to produce recycled materials and/or products. The fourth column indicates the energy savings by using recycled materials instead of virgin materials.

TABLE 5.2 CRADLE-TO-GATE ENERGY REQUIREMENTS OF VIRGIN AND RECYCLED MATERIALS GENERATED IN AIRCRAFT MANUFACTURING PLANTS.

Recyclable Aircraft Material	**Cradle-to-Gate Energy for New Materials Production (MJ/kg)**	**Energy to Produce Recycled Materials (MJ/kg)**	**Energy Saved (MJ/kg)**	**References**
Aluminum	Primary energy: 47	2.4	44.6	(BIR, 2008)
Batteries (all types such as dry cell, NiCd, lead acid, etc.)	PbA: 23.4–38	9–14[a]	19.2	(Rydh and Sanden, 2005)
	NiCd: 90–123	22–30[a]	80.5	(Rydh and Sanden, 2005)

Recyclable Aircraft Material	Cradle-to-Gate Energy for New Materials Production (MJ/kg)	Energy to Produce Recycled Materials (MJ/kg)	Energy Saved (MJ/kg)	References
				(Rydh and Karlstrom, 2002)
	NiMH: 128–241	21–40[a]	154	(Rydh and Sanden, 2005)
	NCA-G: 149–224	25–37[a]	155.5	(Rydh and Sanden, 2005)
	NaS: 144–163	30–34[a]	121.5	(Rydh and Sanden, 2005)
Blast media group	Steel (BF and BOF): 23	—	—	(Norgate et al., 2007
	Primary energy steel (BF-BOF): 14 Primary energy steel (DRI + EAF): 19.2	Steel (EAF): 11.7	BF-BOF: 2.3 DRI+EAF: 7.5	(BIR, 2008)
Cardboard	20	–58	78	(Overcash, 2013)
Caustic solutions	KOH: 18.3	—	—	(Esmaeili, 2013)
	NaOH: 17.73[1]	0.8[2]	16.93	(Franklin Associates, 2011)[1] (Simpson et al., 1988)[2]
Coated wire	Pyrometallurgy from ore concentrate: 16.9[1] Hydrometallurgy from oxide ores: 25.5[1]	Production from scrap: 6.3[2]	Pyrometallurgy: 10.6 Hydrometallurgy: 19.2	(European Copper Institute)[1] (BIR, 2008)[2]
Composites	CFRTS: 234 CFRTP: 155	CFRTS: 33 CFRTP: 15	CFRTS: 201 CFRTP: 140	(Suzuki and Takahashi, 2005)
Construction/ demolition debris	Concrete: 1.11[1] Aggregate: 0.083[1]	Concrete: 0.095[2]	1.015	(Greenspec, 2012)[1] (Hameed and Chini, 2010)[2]
Electronics	—	—	—	—
Ferrous metal (steel)	See entry for steel under blast media	—	—	—
Florescent lamps	Compact florescent	—	—	(OSRAM, 2012)

Recyclable Aircraft Material	Cradle-to-Gate Energy for New Materials Production (MJ/kg)	Energy to Produce Recycled Materials (MJ/kg)	Energy Saved (MJ/kg)	References
	lamp: 14,688 (CED of production phase)			
Food waste and trash	8.4[1]	Composting: 0.098[2]	8.3	(Heller and Keoleian, 2000)[1] (Levis, 2008)[2]
Gloves	Latex: 20.9[1]	—	11.5[2] (saved energy by rubber burning)	(Esmaeili, 2013)[1] (Morris, 1996)[2]
Kevlar	720 (production energy)	—	—	(Kirkland, 2008)
Nonferrous metal (not aluminum) (titanium, copper)	See coated wires entry for copper	—	—	—
Oil	10[1]	—	6.6[2]	(Gutowski et al., 2012)[1] (DOE, 2006)[2]
Paints (outdated)	Water-borne paint: ≈94.4 Solvent-borne paint: 155.2 (primer+top coat)	—	—	(Greenspec, 2012)
Paint-contaminated solids	20	–58	78	(Overcash, 2013)
Paper	See entries for cardboard and paint-contaminated solids	—	—	—
Plastic bottles from employees	42.2[1] PET: 36[2]	PET: 31[2]	5	(Esmaeili, 2013)[1] (Griffing, 2012)[2]
Plastics from all industrial operations	PVC: 21.6[1] PP: 33[1] PET: 36[2]	PET: 31[2]	5	(Esmaeili, 2013)[1] (Griffing, 2012)[2]
Solvents	—	—	—	—
Tin	Primary production: 18.2	Production from recycled: 0.2	18	(BIR, 2008)

Recyclable Aircraft Material	Cradle-to-Gate Energy for New Materials Production (MJ/kg)	Energy to Produce Recycled Materials (MJ/kg)	Energy Saved (MJ/kg)	References
Tires	80[1]	—	14.77[2] (saved energy by burning)	(Lutsey et al., 2006)[1] (Morris, 1996)[2]
Toner cartridges	38	close to zero	38	(Ahmadi et al., 2003)
Tyvek suits	High density polyethylene: 73.7	—	—	(Momani, 2009)
Wood	Glulam: 11.08[1] Lumber (KD): 8.97[1] LVL: 8.85[1] Plywood: 7.57[1]	—	6.4[2]	(Puettmann and Wilson, 2005)[1] (Morris, 1996)[2]

BF-BOF: Blast furnace/basic oxygen furnace
CED: Cumulative energy demand
Cu: Copper
CFRTP: Carbon fiber-reinforced thermoplastic
CFRTS: Carbon fiber-reinforced thermoset
DRI+EAF: Direct reduction/electric arc furnace
LVL: Laminated veneer ***lumber***
NaS: Sodium-sulfur battery
NaOH: Sodium hydroxide
NCA-G: Lithium-ion battery
NiCd: Nickel-cadmium battery
NiMH: Nickel-metal hydride battery
NiO: Nickel oxide
PbA: Lead acid battery
PE: Polyethylene
PET: Polyethylene terephthalate
PVC: Polyvinyl chloride
TPS: Thermoplastic starch

[a] Reported as material production energy using recycled materials.

In the present study, CO_2 emissions were analyzed to determine the effects of using recycled versus virgin materials, as shown in Table 5.3.

TABLE 5.3 AMOUNTS OF GENERATED AND SAVED CO_2 EMISSIONS FROM REPLACING VIRGIN WITH RECYCLED MATERIALS.

Recyclable Aircraft Material	CO_2 Generated by Virgin Material Production (kg CO_2/kg material)	CO_2 Generated by Recycled Material Production (kg CO_2/kg material)	CO_2 Saved by Recycling (kg CO_2/kg material)	Reference

Recyclable Aircraft Material	**CO$_2$ Generated by Virgin Material Production (kg CO$_2$/kg material)**	**CO$_2$ Generated by Recycled Material Production (kg CO$_2$/kg material)**	**CO$_2$ Saved by Recycling (kg CO$_2$/kg material)**	**Reference**
Aluminum	Primary production: 3.83	Production from recycled: 0.29	3.54	(BIR, 2008)
Batteries	PbA: 15	0.604[a]	14.4	(Ishihara et al., 1999)
	NiCd: 3.1–3.2	1.32–1.8[a]	1.59	(Rydh and Sanden, 2005)
	NiMH: 14.8[1]	1.18[2–a]	13.62	(Sullivan and Gaines, 2010)[1] (Ishihara et al., 2010)[2]
	NaS: 11.6–13.2	8.64–9.78[a]	3.19	(Rydh and Sanden, 2005)
	Li-ion: NCA-G: 18.1[1] NCA-G: 18.2[2]	1.5–2.22[1–a] 0.29[2–a]	≈16[1] ≈17.9[2]	(Rydh and Sanden, 2005)[1] (Ishihara et al., 1999)[2]
Blast media group	Steel primary (BF/BOF route): 2.3[1] Steel primary (BF route): 1.54[2]	Production from recycled: 0.68[2]	Steel: 1.62	(Norgate et al., 2007)[1] (Universe Project, 2012)[2]
Cardboard	1.22	–3.45	4.67	(Overcash, 2013)
Caustic spent aqueous solutions	NaOH: 0.074	—	—	(Franklin Associates, 2011)
Coated wire	Pyrometallurgy from ore concentrate: 1.25 Hydrometallurgy from oxide ores: 1.57	0.44	Pyrometallurgy: 0.81 Hydrometallurgy: 1.13	(European Copper Institute, 2012)
Composites	12	2	10	(Rydh and Sun, 2005)

Recyclable Aircraft Material	**CO_2 Generated by Virgin Material Production (kg CO_2/kg material)**	**CO_2 Generated by Recycled Material Production (kg CO_2/kg material)**	**CO_2 Saved by Recycling (kg CO_2/kg material)**	**Reference**
Construction/ demolition debris	Concrete: 0.159[1] Aggregate: 0.0048[1]	Concrete: 0.009[2]	Concrete: 0.15	(Greenspec, 2012)[1] (EPA.GOV, 2012)[2]
Electronics	—	—	—	—
Ferrous metal such as steel	See entry for blast media			
Florescent lamps	Production phase: 0.88	—	—	(OSRAM, 2012)
Food waste and trash	≈0.504	0.00625	0.5	(Levis, 2008)
Gloves	Latex: 1.254	—	—	(Esmaeili, 2013)
Kevlar	N/A	N/A	N/A	N/A
Nonferrous metal (not aluminum) (titanium, copper)	Pyrometallurgy from ore concentrate: 1.25 Hydrometallurgy from oxide ores: 1.57	Production from scrap: 0.44	Pyrometallurgy: 0.81 Hydrometallurgy: 1.13	(BIR, 2008)
Oil	—	—	—	—
Paints (outdated)	Water-borne paint: 3.4 Solvent-borne paint: 5.00	—	—	(Greenspec, 2012)
Paint-contaminated solids	See entries for cardboard and paint-contaminated solids	—	—	—
Paper	See entry for cardboard	—	—	—
Plastic bottles	PE: 1.69 PET: 4.10	PE: 0.50 PET: 0.47	PE: 1.19 PET: 3.63	(Universe Project, 2012)

Recyclable Aircraft Material	CO_2 Generated by Virgin Material Production (kg CO_2/kg material)	CO_2 Generated by Recycled Material Production (kg CO_2/kg material)	CO_2 Saved by Recycling (kg CO_2/kg material)	Reference
Plastics from all industrial operations	See entry for plastic bottles			
Solvents	—	—	—	—
Tin	Primary production of tin: 2.18[b]	Production from recycled: 0.024[c]	2.156	(BIR, 2008)
Tires	3.39	Retread: 2.36	1.03	(Remanufacturing.org, 2013)
Toner cartridges	2.37	close to zero	≈2.37	(Ahmadi et al., 2003)
Tyvek suits	High density polyethylene: 2.5	—	—	(Momani, 2009)
Wood	Waste wood: 0.78	Chip board: 0.01	Chip board: 0.77	(Universe Project, 2012)

BF-BOF: Blast furnace/basic oxygen furnace
CED: Cumulative energy demand
Cu: Copper
CFRTP: Carbon fiber-reinforced thermoplastic
CFRTS: Carbon fiber-reinforced thermoset
DRI+EAF: Direct reduction/electric arc furnace
LVL: Laminated veneer ***lumber***
NaS: Sodium-sulfur battery
NaOH: Sodium hydroxide
NCA-G: Lithium-ion battery
NiCd: Nickel-cadmium battery
NiMH: Nickel-metal hydride battery
NiO: Nickel oxide
PbA: Lead acid battery
PE: Polyethylene
PET: Polyethylene terephthalate
PVC: Polyvinyl chloride
TPS: Thermoplastic starch

[a] Emissions factor, CTG included electric energy: 0.06 kg CO_2 equivalent/MJ.
[b] Based on emissions of 0.12 kg CO_2/MJ, as found in processes with similar chemistry.
[c] Based on melting recovery using UK average electricity emission factor to estimate CO_2 emissions.

The following section provides a description of the potentially recyclable materials.

Aluminum: Aluminum is one of the most energy intensive materials (MJ/kg) (Green, 2007). According to the Bureau of International Recycling (BIR) the energy requirement of primary aluminum production is 47 MJ/kg, which includes bauxite mining, alumina production/Bayer process, Hall-Heroult process, electrolysis, and casting. The energy requirement for recycled aluminum production is only 2.4 MJ/kg (BIR, 2008). The energy savings from recycling aluminum is 44.6 MJ/kg (Table 5.2).

According to the BIR, the carbon footprint for the primary production of aluminum is 3.83 kg CO_2/kg aluminum. The carbon footprint for the recycled production of aluminum is only 0.29 kg CO_2/kg aluminum (Table 5.3). This is a savings of 92% CO_2 emissions when aluminum production occurs through recycled/scrap aluminum (BIR, 2008).

Batteries: Batteries are the energy-providing products in aircraft that can be recycled. Sullivan and Gaines (2010) investigated the cradle-to-gate life-cycle energy requirements of batteries, some of which are lead acid battery, nickel-cadmium battery, nickel-metal hydride battery, lithium-ion battery, and sodium-sulfur battery. Each battery may contain different materials and require different production steps. The CTG inventory includes battery manufacturing, production of materials used for batteries, and energy requirements (Sullivan and Gaines, 2010). The possible energy savings from recycled batteries is provided in Table 5.2 (Rydh and Sanden, 2005; Rydh and Karlstrom, 2002).

As shown in Table 5.3, CO_2 emissions generated in CTG battery production are high. The values of CO_2 emissions of the recycled batteries are calculated from the energy requirements of the recycled battery. CO_2 emissions are reduced nearly tenfold for many batteries when recycled battery materials are employed in the production steps.

Blast Media: The blast media group is assumed to be comprised of contaminated chips, tape, and steel media used in paint removal or the stripping process. The four major methods of producing steel are blast furnace/basic oxygen furnace, electric arc furnace, direct reduction, and smelting reduction. The energy requirements for the production of 1 kg steel are 14 MJ/kg for the primary production furnace/basic oxygen furnace route, 19.2 MJ/kg for the primary production direct reduction/electric arc furnace route, and 11.7 MJ/kg for the recycled production electric arc furnace route, as can be seen in Table 5.2 (BIR, 2008). Energy savings from recycled steels usually vary depending on the production methods. In terms of sustainability and quality, steel offers excellent properties, even when it is extensively recycled. Up to 20% of scrap metal can be added to the blast furnace during the primary production of iron from ore. Primary steel production from iron ore produces 1.54 tons of CO_2 per ton of steel; however, by collecting, treating, and processing steel scrap, this amount can be reduced to approximately 0.68 tons of CO_2 per ton of crude steel, which corresponds to a 55% reduction in CO_2 emissions (Universe Project, 2012). According to (Norgate et al., 2007), 2.3 kg CO_2 emission was generated during the production of steel by following blast furnace and basic oxygen furnace integrated routes.

Cardboard and Paper: The cradle-to-gate energy requirement of virgin cardboard production is about 20 MJ/kg. One kg of recycled cardboard saves -58 MJ energy, which includes credits for not landfilling or harvesting trees because the recycled cardboard replaces the virgin cardboard (Overcash, 2013). Thus, the total savings associated with the virgin-to-recycled replacement is 78 MJ/kg. The CO_2 saving is 4.67 kg CO2eq/kg when cardboard is recycled (Table 5.3).

Caustic Solutions: Alkaline hydroxides (e.g., potassium hydroxide, sodium hydroxide, and lithium hydroxide), non-alkaline hydroxides (e.g., ammonium hydroxide , triethylamine, and tetramethylammonium hydroxide) can be used as caustic solutions after mixing with water at about a two-to-three ratio (Sangeeta et al., 2000). Caustic soda (sodium hydroxide—NaOH) and chlorine are generally produced from salt water via electrolytic processes such as a diaphragm cell, mercury cathode cell, or membrane cell, with 66.4%, 8.6%, and 22.9% production rates, respectively. Hydrogen gas evolves during the electrolysis process, which may be beneficial to reduce production costs. Franklin Associates, a Division of Eastern Research Group, Inc., utilized diaphragm/membrane (98.6%) and mercury technologies (1.4%) to produce sodium hydroxide. The cradle-to-gate energy consumption includes the mining operations and NaOH production. The mining of the salt includes 2.15 MJ/kg processing and 0.062 MJ/kg transportation energies, while the production of sodium hydroxide includes 15.36 MJ/kg processing and 0.16 MJ/kg transportation energies, thus totaling 17.73 MJ/kg CTG energy for the entire sodium hydroxide production (Franklin Associates, 2011). Similarly, Esmaeili (2013) defined CTG energy requirements of potassium hydroxide as 18.3MJ/kg (Table 5.2). The energy required to recycle sodium hydroxide solutions is 0.8 MJ/kg (Simpson et al., 1988). When a fossil fuel is used, CO_2 emissions from the production of sodium hydroxide are 0.074 CO_2/ kg (Franklin Associates, 2011).

Coated Wires: Coated wires can be used in many electrical applications of aircraft, including electrical motors, magnetic coils, transformers, insulations, electrical connections, signaling, sensors, etc. Copper is mainly produced using pyrometallurgical and hydrometallurgical processes. The pyrometallurgical process begins with the primary copper ore concentrate, while the hydrometallurgy process begins with soluble copper ions in a copper solution. Metallic copper can also be produced using the scrap/recycled copper at a very low cost (BIR, 2008). Energy savings associated with the recycling of copper vary due to the different production methods (Table 5.2). As can be seen, producing recycled coppers using pyrometallurgy and hydrometallurgy methods saves 10.6 MJ/kg and 19.2 MJ/kg, respectively. The production of copper from scraps requires only 6.3 MJ/kg energy, indicating both energy savings and environmental savings (BIR, 2008).

One kilogram of virgin copper production generates about 1.25 (pyrometallurgical process) to 1.57 (hydrometallurgical process) kg CO_2, while copper production from scrap generates only 0.44 kg CO_2 (European Copper Institute, 2012).

Composite: The cradle-to-gate energy requirement of carbon fiber-reinforced thermoplastic is about 155 MJ/kg, which involves carbon fiber production, resin production, and the molding process (Suzuki and Takahashi, 2005). The energy intensity of recycling carbon fiber-reinforced thermoplastic was 15 MJ/kg, which includes recovering the carbon fiber-reinforced thermoplastic and die molding (Table 5.2) (Suzuki and Takahashi, 2005).

Another composite example is carbon fiber-reinforced thermoset production. The energy intensity of carbon fiber-reinforced thermoset was 234 MJ/kg, which requires carbon fiber, epoxy resin, and a resin transfer molding process (Table 5.2). The energy consumption of the recycled carbon fiber-reinforced thermoset was 33 MJ/kg, including carbon fiber recovery, polypropylene, and matched die molding methods (Suzuki and Takahashi, 2005). Energy savings associated with the production of composites from recycled materials are 201MJ/kg for carbon fiber-reinforced thermoset and 140 MJ/kg for carbon fiber reinforced-thermoplastic (Table 5.2). According to Rydh and Sun (2005), the cradle-to-gate CO_2 emissions of composite are 12 kg, and the recycled fibers is about 2 kg CO_2 emissions.

Construction/Demolition Debris: Construction/demolition debris, such as concrete, asphalt, wood, sand, gravel, and other soils, are all recyclable components. Concrete is a mixture of aggregate, cement, and water at different ratios depending on the conditions and applications. As the result of environmental awareness, limitations in landfill allocations, governmental laws, and economic benefits, concrete recycling is becoming more important worldwide. Usually, concrete is collected after the cleaning of trash, wood, paper, and unwanted metallic materials using separators, and then it is fed into a crusher to create different sizes of construction products. The CTG requirements of concrete and aggregates are 1.11 MJ/kg and 0.083 MJ/kg, respectively (Anonymous 1; Greenspec, 2012).

The energy consumption of concrete recycling consists of the energy values of transporting concrete to the crusher location and crushing the demolished material. Crushing aggregates requires 0.082 MJ/kg, while the transportation of material for every 100 km requires 0.265 MJ/kg. The roundtrip distance is typically about 5 km, so the energy needed to recycle 1 kg of concrete aggregate is 0.095 MJ/kg (Hameed and Chini, 2010).

The cement industry is one of the major producers of CO_2 emissions in the world because of the calcination of calcium carbonate (direct source) and use of energy during cement production (indirect source). Producing concrete and aggregate releases 0.159 kg and 0.0048 kg CO_2 emissions, respectively (Greenspec, 2012), while recycling concrete releases only 0.009 kg CO_2 (EPA.GOV, 2012). According to Giustozzia et al., 2012 recycling airport pavements save 35% emission compared to the virgin production (Giustozzia et al., 2012).

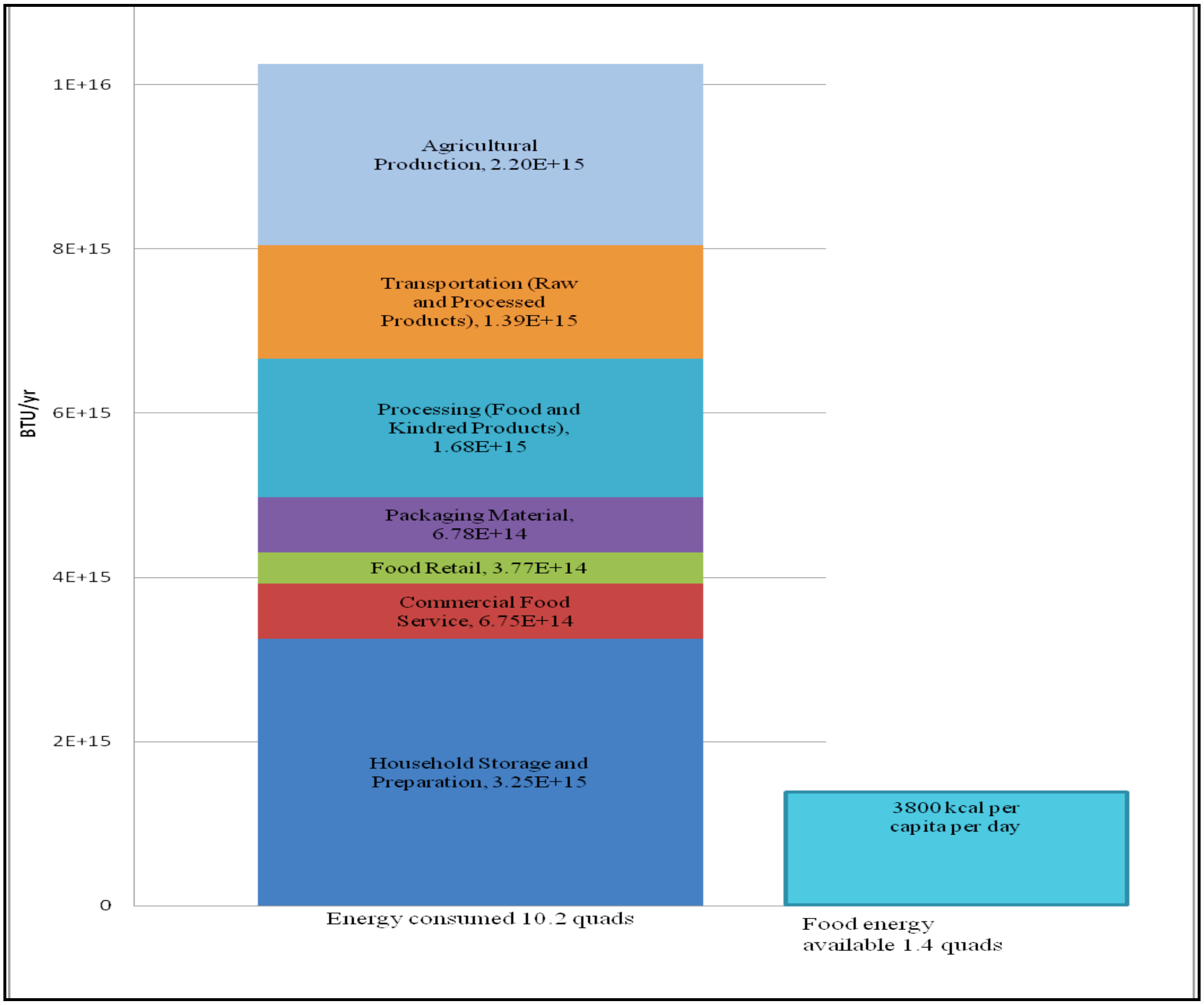
Electronics: All waste from electrical and electronic equipment and parts should be recycled because of higher economic values and environmental concerns. The new generation of small- and large-scale aircraft is highly sophisticated and involves many electronics, which need to be recycled or properly disposed of (Anonymous 2, 2012). Although the production of electronic materials and devices used by the aircraft manufacturing industry require very high energy demands, no clear recycling rates and reduction in carbon footprint emissions are provided by the companies and research scientists.

Ferrous Metals and Steels: Information on these materials can be found in the earlier discussion of steel in the Blast Media section.

Florescent Lamps: Table 5.2 provides the energy consumption of a fluorescent lamp during production. This type of lamp usually contains liquid mercury (~2.5 mg or more) and is often subjected to public safety and scrutiny. Florescent lamps are intended to be recycled to prevent environmental pollution, but these mercury-containing products are not included in this life-cycle analysis (OSRAM, 2012). According to Osram (2012), the production of florescent lamps generated about 0.88 kg CO_2.

Food Waste and Trash: A variety of food is served to the workers and engineers during aircraft production. There are many ways to recycle food and food products based on the condition, such as edible food donation or food composting. Figure 5.1 represents the energy requirement that goes into the food supply in the U.S. The cradle-to-gate energy requirement of the food supply in the U.S. can be calculated by the following steps: seed production or animal breeding, agricultural production, transportation (crop field to factory), processing, and packaging.

In 1995, the U.S. food supply included exports (355,560 x 10^6 lbs), crop production (921,590 x 10^6 lbs), animal products (239,470 x 10^6 lbs), feed to livestock and poultry (964,000 x 10^6 lbs), and edible food supply (355,880 x 10^6 lbs), totaling about 2,836,500 x 10^6 lbs. This production required 10.2×10^{15} Btu energy, so as an initial estimate, 1 kg of food requires 8.4 MJ energy (Heller and Keoleian, 2000). Food recycling has both economic and social benefits. For businesses, it lowers the garbage bill, qualifies for a tax deduction, inspires employee pride, and shows the community that the local business cares (Kingcounty.gov., 2012). Levis (2008) analyzed the composting of food and yard waste using the aerated static piles method, which requires 0.098 MJ/kg waste. This energy covers the energy used for shredding, screening, dumping from the front end loaders. Composting food and waste released 0.00625 kg CO_2/kg (Levis, 2008). CO_2 value of virgin food production is calculated by multiplying the virgin food energy value by 0.06 kg CO_2/MJ primary energy use (Table 5.3).



Source: (Heller and Keoleian, 2000), http://css.snre.umich.edu/css_doc/CSS00-04.pdf

Figure 5.1 Life-cycle demands supplied for U.S. food.

Gloves: The cradle-to-gate life cycle of latex gloves starts with the harvesting of latex from rubber trees. After quality control, latex gloves are injection molded into hand shapes during manufacturing (Repertoire, 2001). The CTG life-cycle energy requirement of the latex glove is 20.9 MJ/kg (Esmaeili, 2013). Burning rubber to produce steam and then electricity saves 11.5 MJ/kg energy (Morris, 1996). According to Esmaeili (2013) the CTG CO_2 emissions of latex gloves are 1.254 kg CO_2/kg latex gloves.

Kevlar: Kevlar is a very high strength and fire-resistant fiber that is used in many aircraft industries. According to Kirkland (2008), the energy production of Kevlar is 720 MJ/kg. CO_2 generation during Kevlar fiber production is not available currently.

Nonferrous Metals (Titanium and Copper): The energy discussion of copper is given previously under the section for Coated Wires. Considering a virgin-recycled replacement, the CO_2 saving is 0.81 kg, if the pyrometallurgy method is used, and 1.13 kg if the hydrometallurgy method is used (BIR, 2008).

Oil and Oil Products: According to Gutowski et al. (2012), the primary energy needed for oil production is 10 MJ/kg. Considering fuel-burning and re-refining processes, the energy savings from recycled oil is between 745,000 Btu/barrel (6.6 MJ/kg) and 1,722,000 Btu/barrel (15.2MJ/kg) (DOE, 2006).

Paints (Outdated): The energy requirement for producing water-borne paint is 94.4 MJ/kg, while solvent-borne paint requires 155.2 MJ/kg (Greenspec, 2012). The production of water-borne and solvent-borne paints generates 3.4 kg CO_2 and 5.00 kg CO_2, respectively (Greenspec, 2012). CO_2 emissions of paint-contaminated solids vary, depending on the amount and types of contaminants.

Paint-Contaminated Solids: The examples of this category are paper and similar products that are used to protect areas on a plane during the painting process.

Paper: The energy and CO_2 values are assumed to be similar to cardboard as presented previously in that section.

Plastic Drink Bottles: Virgin production of polyethylene terephthalate bottle requires 36 MJ/kg, while recycled production requires 31 MJ/kg. Thus, the savings by replacing virgin bottles to recycled bottles is 5 MJ/kg (Griffing, 2012). Considering a virgin-recycled replacement, CO_2 production of a recycled polyethylene bottle is 1.19 kg, while a virgin polyethylene terephthalate bottle is 3.63 kg (Table 5.3) (Universe Project, 2012).

Plastics from All Other Industrial Operations: This category of materials mainly includes plastics used for packaging of shipments/delivery, storage, blow molding, plastic containers, etc. According to Esmaeili, (2013), the cradle-to-gate energy consumption of polypropylene and polyvinyl chloride are 33 MJ/kg and 21.6 MJ/kg, respectively. The remaining information for this category of materials is the same as for the Plastic Drink Bottle entry.

Solvents: Various solvents are utilized during the manufacture and maintenance of aircraft. The solvents used for aircraft manufacturing include solvents used for cleaning, composite manufacturing, metal working/cutting/machining, sealants and adhesives, and tires (for the adhesion between the different parts and rubbers). Additionally, some solvents are used as fire-retardant chemicals, as well as for crack detection, de-icing, jet-fuel additives, and landing gear lubricants (European Solvents

Industry Group, 2006). Even though solvents are one of the major products in aircraft manufacturing, CO_2 emission values from cradle-to-gate are not provided in detail.

Tin: Primary tin production consists of ore (cassiterite) mining, concentration (mineral processing), roasting (smelting), reduction, electrolytic refining, and then metallic tin production. Recycled tin production utilizes scrap tin that is melted and refined (similar to the electrolytic refining process). The energy requirement of tin from mining to the refining processes is about 200 MJ/kg (BIR, 2008). The energy savings from recycling tin material is 18 MJ/kg (Table 5.2) The primary production of tin generates 2.18 kg CO_2 /kg tin metal, whereas the production from recycled tin generates only 0.024 kg CO_2 /kg (BIR, 2008).

Tires: The cradle-to-gate energy requirements of a tire consist of material acquisition and processing (68.12MJ/kg) and tire manufacturing (11.68MJ/kg). Thus, the total energy to produce a tire is 80 MJ/kg (Lutsey et al., 2006). The easiest way to recycle a tire, if it is in suitable condition, is to retread and reuse. Retreading a tire requires about 30% of the energy of a new tire (Kent, 2010). Burning tires to produce steam and then electrical energy saves 14.77 MJ/kg (Morris, 1996). On the basis of materials, transportation, and energy values, producing one kg of new tire creates 3.39 kg CO_2 emissions compared to 2.36 kg CO_2 for retreading one kg of tire, which saves 1.03 kg CO_2 emissions per kg of tire (Remanufacturing.org, 2013).

Toner Cartridges: The cradle-to-gate energy consumption for toner includes carbon black (1.5×10^6 kJ), magnetite (2.9×10^6 kJ), resin (4.7×10^6 kJ), toner (22×10^6

kJ), and production, and transportation (raw material to toner manufacturer) (3.4 x 10^6 kJ). Overall, the CTG energy consumption of a toner cartridge is 34.5 x 10^6 kJ/mton ≈ 35 MJ/kg. On the other hand, recycling toner requires almost no energy, which provides a very high energy savings for toner cartridge reproduction (Ahmadi et al., 2003). Ahmadi et al. (2003) stated that the emissions factor in toner production is 2.37 kg CO_2 per kg of toner. CO_2 emissions result from carbon black production, magnetite production, resin production, toner manufacturing, and transportation from the raw material to the toner manufacturing facility (Nelson et al., 2011).

Tyvek Suits: These protective suits are durable spun-bonded olefin sheet products made of high-density polyethylene fibers. Depending on the size/weight of the suit, each one is approximatelly150 g–190g (DuPont, 2012). The energy requirement (production and feedstock) for high-density polyethylene production is 73.7 MJ/kg (Momani, 2009). According to Momani (2009), high-density polyethylene creates 2.5 kg CO_2 /kg polymer (Momani, 2009).

Wood: The cradle-to-gate cumulative energy of structural wood products varies, depending on the regions (e.g., Pacific Northwest and Southeast). The total electricity allocations include harvesting, product manufacturing, and transportation of logs and other materials to production facilities. CTG energy requirements are for wood products such as glulam (11.08 MJ/kg), lumber (8.97 MJ/kg), laminated veneer ***lumber*** (8.85 MJ/kg), and plywood (7.57 MJ/kg) (Puettmann and Wilson, 2005). Using recycled wood instead of virgin wood in the manufacturing of particle board saves about 6.4 MJ/kg of waste (Morris, 1996).

It is reported that recycled waste wood and other similar materials (e.g., wood chips, packaging materials, bark, sawdust, etc.) can be used to generate electricity and heat to lower the overall cost of production. Recycled waste wood and other sources can be primary and secondary sources. When considering both approaches together, approximately 0.77 kg of CO_2 can be reduced, as shown in Table 5.3 (Universe Project, 2012).

5.4.2 Recycling Benefits of Local Aircraft Companies

As stated earlier, recycling yields numerous benefits by reducing emissions (air, water, soil) and the use of natural resources. Recycling also reduces the energy used for production of the materials Table 5.2 because recycling or secondary production from scrap material requires less energy compared to that required for virgin material. As shown in Table 5.4 the total energy savings from aircraft manufacturing facilities in Wichita in 2009 is 840.8million MJ/year. As of 2013, the estimated annual electricity usage per household in Wichita is about 80,000 MJ (WestarEnergy, 2013). As of 2010 there are 151,818 households in Wichita, KS (Wikipedia.org, 2013)The energy saving that defined here will be sufficient enough to sustain the yearly consumption of 10,510 households. This offsets about 8% of all Wichita household energy usage per year. If all data for the energy for recycled components of aircraft in Wichita were available, this amount would increase, indicating a huge energy savings. Similarly, a much larger benefit would occur if the percentage of scrap that is recycled were increased from the approximate level of 20%.

TABLE 5.4 RECYCLING ENERGY SAVINGS FROM AIRCRAFT MANUFACTURING FACILITIES IN WICHITA IN 2009 (1,765 PLANES AND 1,029 MAJOR COMPONENTS).

Recyclable Aircraft Material	Total Recycled Material (kg)	Virgin Material (MJ/kg)	Recycled Material (MJ/kg)	Replacement with Virgin Material (MJ/kg)	Total Energy Savings (million MJ/ year)*
Aluminum	11,142,988	47	2.4	44.6	497.0
Construction/ demolition debris	6,204,730	1.11	0.095	1.015	6.3
Food waste and trash	2,800,486	8.4	0.098	8.3	23.2
Solvents	2,775,529	—	—	—	—
Caustic spent aqueous solutions	2,125,260	NaOH: 17.73	0.8	16.93	36.0
Ferrous metal (steel)	1,528,682	DRI+EAF: 19.2	Steel (EAF): 11.7	DRI+EAF: 7.5	11.5
Paper	1,132,948	20	–58	78	88.4
Wood	1,128,048	Glulam: 11.08	—	6.4	7.2
Cardboard	976,654	20	–58	78	76.2
Oil	754,017	10	—	6.6	5.0
Nonferrous metal (not aluminum)	741,790	25.5	6.3	Hydrometallurgy: 19.2	14.2
Blast media group	351,806	DRI+EAF: 19.2	Steel (EAF): 11.7	DRI+EAF: 7.5	2.6
Paint-contaminated solids	331,349	20	–58	78	25.8
Composites	216,817	CFRTS: 234	33	201	43.6
Plastic bottles	102,648	36	31	5	0.5
Plastics from all	99,337	36	31	5	0.5

Recyclable Aircraft Material	**Total Recycled Material (kg)**	**Virgin Material (MJ/kg)**	**Recycled Material (MJ/kg)**	**Replacement with Virgin Material (MJ/kg)**	**Total Energy Savings (million MJ/ year)***
industrial operations					
Paints (outdated)	28,236	—	—	—	—
Electronics	15,429	—	—	—	—
Batteries (all types)	15,120	NCA-G: 187	31	156	2.4
Florescent lamps	9,466	—	—	—	—
Coated wire	8,954	25.5	6.3	Hydrometallurgy: 19.2	0.17
Tires	5,445	80	—	14.77	0.08
Tyvek suits	3,402	—	—	—	—
Toner cartridges	3,261	35	about zero	35	0.12
Tin	2,431	18.2	0.2	18	0.04
Gloves	907	20.9	—	11.5	0.01
Kevlar	482	—	—	—	—
TOTAL	**32,506,224**	—	—	—	**840.8**

*Total energy savings calculated based on maximum values.

In addition, the reduction in CO_2 emissions in Wichita in 2009 was 61.1 million kg/year, as shown in Table 5.5 According to the U.S. Environmental Protection Agency, an average vehicle has tailpipe CO_2 emissions of about 5.1 metric tons (or 5,100 kg/12,000 miles) per year (EPA.GOV, 2011). Based on our calculations, the CO_2 savings is equivalent to the yearly tailpipe CO_2 generation in 11,980 average vehicles. Looking at Table 5.1, we can see that the aircraft manufacturers have an even higher potential for recycling since only about 20% of the scrap materials are currently recycled.

TABLE 5.5 CO$_2$ REDUCTION AS RESULT OF RECYCLING IN LOCAL AIRCRAFT COMPANIES IN WICHITA IN 2009.

Recyclable Aircraft Material	**Total Recycled Material (kg/yr)**	**Virgin Material (kg)**	**Recycled Material (kg)**	**Replacement with Virgin Material (kg)**	**Total CO$_2$ Savings (million kg/ year)**
Aluminum	11,142,988	3.83	0.29	3.54	39.4
Construction/ demolition debris	6,204,730	0.159	0.009	0.15	0.93
Food waste and trash	2,800,486	≈0.504	0.00625	0.5	1.4
Solvents	2,775,529	—	—	—	—
Caustic spent aqueous solutions	2,125,260	—	—	—	—
Ferrous metal (steel)	1,528,682	Steel: 2.3	0.68	1.62	2.4
Paper	1,132,948	1.22	-3.45	4.67	5.3
Wood	1,128,048	Waste wood: 0.78	Chip board: 0.01	Chip board: 0.77	0.87
Cardboard	976,654	1.22	-3.45	4.67	4.6
Oil	754,017	—	—	—	—
Nonferrous metal (not aluminum)	741,790	Cu: 1.57	0.44	1.13	0.84
Blast media group	351,806	Steel: 2.3	0.68	1.62	0.57
Paint-contaminated solids	331,349	1.22	-3.45	4.67	1.5
Composites	216,817	12	2	10	2.2
Plastic bottles from employees	102,648	PET: 4.10	0.47	3.63	0.37
Plastics from all industrial operations	99,337	PET: 4.10	0.47	3.63	0.36
Paints (outdated)	28,236	—	—	—	—
Electronics	15,429	—	—	—	—
Batteries (all types)	15,120	NCA-G: 18.2	0.29	17.91	0.27
Florescent lamps	9,466	—	—	—	—
Coated wire	8,954	Hydrometallurgy: 1.57	0.44	1.13	0.01
Tires	5,445	3.39	2.36 (retread)	1.03	0.056
Tyvek suits	3,402	—	—	—	—

Recyclable Aircraft Material	Total Recycled Material (kg/yr)	Virgin Material (kg)	Recycled Material (kg)	Replacement with Virgin Material (kg)	Total CO_2 Savings (million kg/ year)
Toner cartridges	3,261	2.37	about zero	2.37	0.0077
Tin	2,431	2.18	0.024	2.16	0.0053
Gloves	907	—	—	—	—
Kevlar	482	—	—	—	—
TOTAL	**32,506,224**	—	—	—	**61.1**

*Total CO_2 savings calculated by considering maximum values.

5.5 CONCLUSIONS

The purpose of this study was to analyze the recycling efforts of aircraft companies in Wichita, Kansas, in terms of life-cycle assessments, with a focus on cradle-to-gate energy and greenhouse gas emissions (CO_2). The outcome of this study indicated that recycling aircraft materials from aircraft manufacturing plants provides substantial economic and environmental benefits to the local community. As a result, energy savings (840.8 million MJ/year) from the current recycling of aircraft materials can power 10,510 households in annual electricity consumption in this city. The reduction in CO_2 emissions associated with aircraft material recycling (61.1 million kg) is equivalent to the yearly tailpipe CO_2 generation in 11,980 average vehicles. These savings occur because the energy used for the production of recycled materials is considerably less and also generates much smaller amounts of CO_2 emissions, compared to the production of virgin materials. These benefits also lead to economically viable materials and supplies, which in turn offer sustainable manufacturing of aircraft in Wichita.

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CHAPTER 6

SUMMARY AND CONCLUSIONS

In this chapter, the important findings of this dissertation are summarized and possible future works are highlighted. The results of these four studies can be considered for many other manufacturing industries, such as automotive, electric and electronics, computers, telecommunications, ships, wood, paper, food, textiles, cosmetics, paint, defense, and so on. Below is a quick summary of those studies and their applications:

6.1 MAJOR FINDING of THE STUDIES

Paper 1: “Life Cycle and Nano-products: End-of-life Assessment” analyzed the end-of-life fate of various nanomaterials and nanoproducts. There are 1,014 nanoproducts in the market that were analyzed in this study. Among the whole 1,014 nanoproducts, about 40% of them can be recycled and reused. Accordingly, many industries can utilize our results and expertise to design new manufacturing options for their sustainable production and growth.

Paper 2: “Recycling of Fiber-Reinforced Composites and Direct Structural Composite Recycling Concept” focuses on the composite recycling technologies based on the recycled fiber strengths. We analyzed current recycling methodologies (mechanical, chemical and thermal) for the different composites. Among the current recycling methodologies, the chemical recycling technique offers the highest tensile strength values of the fibers that can be used to produce new high-strength composites (generally 98% strength of virgin fibers). The mechanical recycling technology provides the second-highest-strength fibers (about 75% strength of virgin fibers) and composites. The thermal recycling methodologies yield the fibers that have 50–75% less tensile strengths compared to the virgin fibers. We believe that these results can be strongly considered by many companies to recycle composites because they are expensive and require high energy intensity to produce new composites.

Paper 3: "Recycling of Aircraft: State of the Art in 2011" provides detailed information on the life cycle benefits of many aging/retired aircraft worldwide. This paper states that recycling aircraft is economically and environmentally more responsible than other options. Most of the aircraft materials and components are high tech and require too much energy to produce. Therefore, these materials can be recycled up to 85%. The present paper provides information about the recyclability of the aircraft materials. This can open up new possibilities for sustainable manufacturing in the same or different industries

Paper 4: "Evaluation of Recycling Efforts of Aircraft Companies" analyzes aircraft waste material recycling and gives credit to the life cycle benefits of aircraft. Based on the results, it is recommended that every industry should build its own recycling facility/alternatives to maximize their profits for the sustainable manufacturing, as well as the local communities and the environment. Here, energy savings of the five aircraft companies in Wichita is 840.8 million MJ/year, which is enough electricity to power 10,510 average houses in Wichita, KS. The reduction in CO_2 emissions associated with aircraft material recycling (61.1 million kg) is equivalent to the yearly tailpipe CO_2 generation of 11,980 average vehicles with 12,000 miles driven yearly.

Overall, the authors offered several novel ideas which will open up new possibilities for sustainable material flows for advanced manufacturing. Reducing environmental impacts (e.g., air, soil and water contaminants) can be another major outcome of this dissertation.

6.2 FUTURE WORK

During the present studies, the authors evaluated many of the nanomaterials, composites and other advanced materials and devices, and analyzed their EOL, as well as environmental, economic and health issues. In the future, effects of nanomaterials on the product life and marketability, energy requirements of advanced materials and devices, efficient recycling options, and long term effects of the nanomaterials on the environment and health can be studied in detail. Also, other marketability options of recycled materials and components can be sought.