TRACKING THE LIFE CYCLE OF CONSTRUCTION STEEL: THE DEVELOPMENT OF A RESOURCE LOOP

BY

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Submitted to the graduate degree program in Civil, Environmental and Architectural Engineering and the Graduate Faculty of the University of Kansas School of Engineering in partial fulfillment of the requirements for the degree of Master of Science

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Abstract

Cradle-to-grave model is established on the assumption of a model of one-way, linear flow of materials in the industrial system. Eco-efficiency, as the design strategy of the cradle-to-grave model, aims to reduce the reliance of industry on resources while decreasing the negative consequences to the environment; but designers do not consider the usefulness of a material after it ends its life cycle. Eco-effectiveness and cradle-to-cradle design present a new concept as an alternative design strategy by modeling material-flow based on biological metabolism processes. This concept assumes that a material will have to be rejuvenated at the end of its functional life, and reused for another use.

Both of those models: cradle-to-cradle and cradle-to-grave, integrate energy and materials in different processes, such as extract, manufacture, transport, install, deconstruct, demolish and dispose of materials. This thesis developed a “resource loop” which represents both the cradle-to-cradle and cradle-to-grave model to accounting materials and energy. Construction steel is chosen as a case study to show the developing processes, and identify “feeds” and “leaks” within the resource loop. The thesis found: 1) The transportation process generates a significant amount of leaks; 2) Materials and energy accounting methods are not comprehensive enough; 3) The resource loop needs to be improved to implement the cradle-to-cradle model in construction industry. In the end of this thesis, some suggestions will be given for future research in implementing the cradle-to-cradle design.

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Chapter 1 Introduction and Background of Research

Sustainability is a broad topic. In 1987, the Brundtland Commission Report for the United Nations defined the sustainability concept as “meeting the needs of the present without compromising the ability of future generations to meet their own needs” (World Commission on Environment and Development, 1987). To achieve sustainability and to make sure our next generation still has enough resources to live on, the United Nations 2005 World Summit Outcome Document highlighted that human should balance between economic growth, ecological impact and social development, which had been characterized in particular as “three pillars”. Research has proved “three pillars” are not mutually exclusive but closely related to each other (Adams, 2006) (Fig.1.1). Among “three pillars”, the economic pillar represents the profit shared by and services for our whole society. The environmental pillar is defined as the negative human impact on the ecosystem. The social pillar pertains to fair and beneficial developments toward labor and the community. The overlapping area in the center represents “Sustainable Development”, which is the balance of “three pillars”.

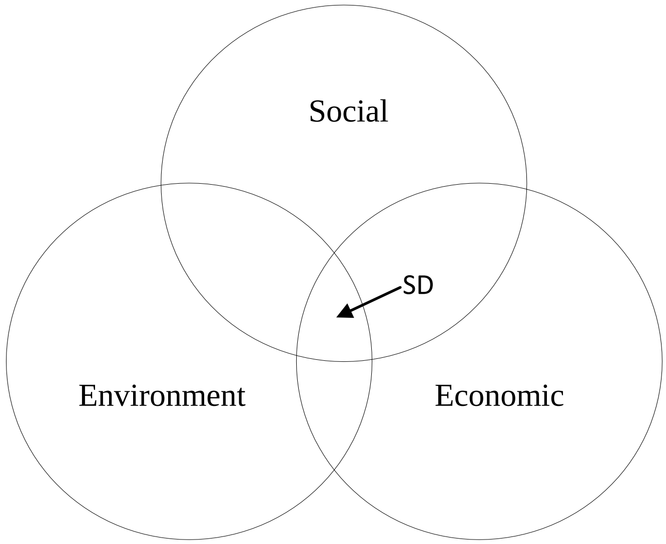

Figure 1.1: Scheme of Interaction of the Three "Pillars" of Sustainable Development (Source: Adams, 2006)

1.1. Sustainable Design

To achieve a balance between the economy, ecology and society, it is necessary to have strategic and sensitive sustainable designs (McLennan, 2005). Sustainable design is a methodology of designing for the economy of resources, products' life cycle, and services for society to comply with the principles of sustainable development (Mann et al., 2005), and it influences all types of industry: ranging from architecture, engineering, construction, manufacturing, all the way to environmental services (Miyatake, 1996). These terms: "energy efficiency", "climate changes", "human footprint", "acid rain", and "carbon footprint" reflect the importance of sustainable design in the industrial systems (Knee, 2007). Many companies have incorporated sustainable design into their business practices. For example, Toyota Motor Engineering and Manufacturing North America, Inc. enhanced their energy management systems and focused on more eco-friendly designs for their products (American Society for Healthcare Engineering of the American Hospital Association, 2006). 3M established the new 3M renewable Energy Division to support advancements in renewable energy markets and offers alternative energy in 3M operations (Smock, 2009).

Implementing sustainable design on a project can be very difficult if there are no reliable benchmarks to measure the level of sustainability. Therefore, many public and private organizations or companies developed different eco-labels for various projects, services and products (Rendall and Chong, 2009). For example, the National Institute of Standard and Technology's (NIST) Building for Economic and Environmental Sustainability (BEES) offers designers the optimal choice of materials that are environmentally friendly and economically sustainable (BEES, 2008). The U.S Environmental Protection Agency (EPA, 2008) and the U.S Department of Energy launched "Energy Star" to evaluate the energy efficiency of electrical products, and thereby help customers save money and minimize the environmental impact through energy efficient products and practices (U.S Department of Energy, 2008). The Carpet and Rug Institute provides "Green Label" and "Green Label Plus" to enhance a high standard for carpet and adhesives to prevent indoor air pollution (The Carpet and Rug Institute, 2009).

1.2. Cradle-to-Grave Model

Starting in the late-nineteenth century and persisting into the twenty-first century, all industrial designed products follow the same process, which is called cradle-to-grave (Jones, 2008). Researchers describe “cradle-to-grave” as a linear, one-way process (Steffen, 2006). In this process, materials are extracted from “cradle”, shaped into products, sold, and eventually disposed of as waste in “grave”— usually in landfills or incinerators, as shown in Figure 1.2 (Graedel 1998). In the cradle-to-grave model, products normally are designed into two categories: products designed to perform certain functions over a fixed period, and the products designed for a longer life cycles. In the first category, the value of the products, such as furniture, glass, or paper, will depreciate throughout their life cycle because of the usage intensity, integrity, and aesthetics. Eventually, products will end up in landfills or incinerators, and their value is considered as zero (McDonough and Braungart, 2002). In the second category, products such as computers, TV or cameras, high labor and material costs are more expensive for repairing or upgrading of those products than to buy a new one; thus, consumers often replace the products entirely, and their value also becomes zero.

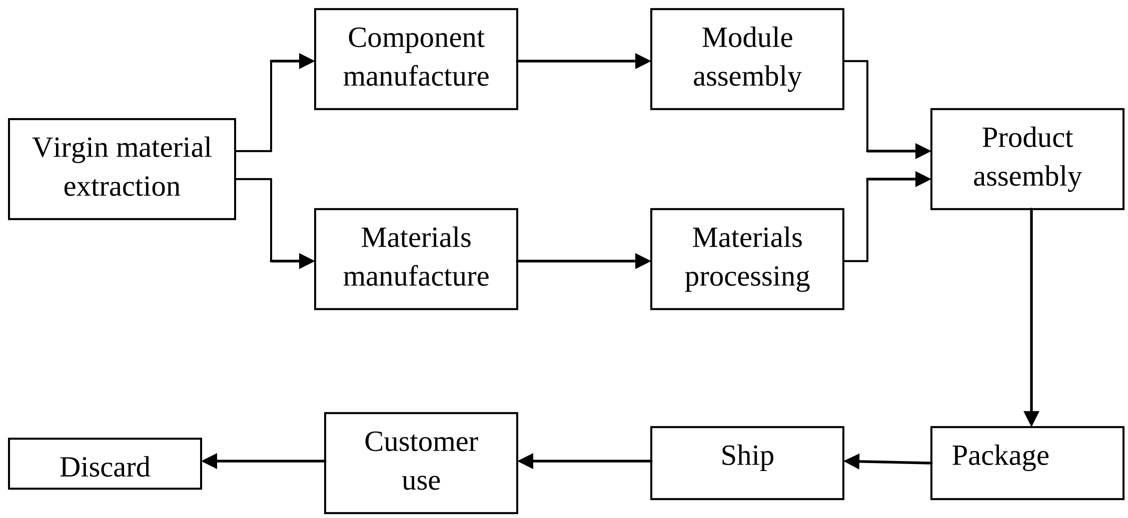

Figure 1.2: Cradle-to-Grave, Linear Materials Flow Model (Source: Graedel, 1998)

To manufacture new products, resources, which include raw materials and energy, are constantly consumed since those zero value products cannot be reused or recycled. In the cradle-to-grave model, wastes, generated during the product's life cycle are defined as post-industrial waste (USGBC, 2005). They are continuously generated at the very beginning of material extraction and last through the life cycle of the product. In addition, when products complete their functions, products, defined as post-consumer, are also turned to waste as they are directly discarded at landfills (USGBC, 2005). Moreover, when sending the post-consumer products to different landfills, transportation will consume much energy.

In the United States, a significant amount of waste is generated each year. For example, 4.39 pounds of trash per day and up to 56 tons of trash per year are generated by an average person (Waste fact, 2009); 59 percent of these wastes are sent straight to the landfills, more than 90 percent of the materials extracted to make durable goods become wastes almost immediately (EPA, 2008). In addition, the wastes generated by the construction industry are about 250 to 300 million tons per year (Lauritzen, 2004).

1.2.1. Eco-Efficiency

To reduce the waste generation and resource consumption, the whole industry adopted eco-efficiency for the cradle-to-grave model (Bleischwitz, 2004). Eco-efficiency aims to diminish the negative environmental impacts by reducing waste generation, raw material extraction, energy and labor cost, and time consumption within product's lifespan (WBCSD, 2000). The term "eco-efficiency" was actually first used by the researchers in 1990 (Kicherer et al, 2007). In 1992, the World Business Council for Sustainable Development (WBCSD) defined eco-efficiency as: "to generate solutions that offer more value than current offerings, while reducing the resource use and environmental impacts throughout a product or service's lifespan" (Sonnemann et al., 2003). Later, Fussler (1996) proposed a goal to cut energy and material-flow to half of 1996 level. Koch (1999) asserts the 80/20 Principle for reducing the effort on the majority of things that do not work very well. In simplest term, eco-efficiency means creating more goods and services with less use of resources, and thus reduces the waste and pollution. The principles of eco-efficiency include:

1. Reduction in the material and energy intensity of goods and services;
2. Reduced dispersion of toxic materials;
3. Improved recyclability;
4. Maximum use of renewable resources;
5. Greater durability of products;
6. Increased service intensity of goods and services (Lovins, 2008).

Eco-efficiency had long been central to most of the environmental agendas imposed by industry (McDonough and Braungart 2002), and a lot of effort were given to reduce the waste to the environment. For example, the weight of a 2-liter plastic soft drink bottle has been reduced from 68 grams to 51 grams over the past decades, which means that 250 million pounds of plastic waste are reduced annually (EPA, 2008). In 2000, more than 55 million tons of Municipal Solid Wastes (MSWs) were reduced in the United States (EPA, 2008). Meanwhile, more and more companies incorporate eco-efficient design strategies as a part of the company culture or mission. For example, the US-based consumer goods manufacturer, 3M, initiated its Pollution Prevention Pays (3P) program in 1975, and accumulates more than US$800 million in the first year (3M, 2005).

Some researchers have proved that eco-efficiency may provide temporary economic advantage in the short term, but lacks the long-term vision of being truly sustainable (Braungart et al., 2006). In "*Cradle to Cradle: Remaking the Way We Make Things*", William McDonough and Michael Braungart stated eco-efficiency as "being less bad" is not good enough (McDonough and Braungart, 2002), as being "less bad" cannot stop the depletion and waste. The cradle-to-grave model determines that the value of a product or material always decreases within the linear, downgrading process (Braungart et al., 2006). Therefore, no matter how efficient a design is, waste is still generated during the manufacturing process, and the useful materials at the end of products' life are discarded as waste. For example, eventually, products, such as furniture, computers, carpets, televisions, clothing, shoes, diapers, paper, wood, and food wastes, will be sent to landfills as their value has been decreasing through their life spans. Even though those post-consumer products can be reused or recycled, their value is so low that they have to be discarded into the landfills. Moreover, "less bad" could be accumulated to cause severe damages. For example, in the 1960s, the now famous publication of "*Silence Spring*" drew large attention to a human-made chemical – DDT, which was accumulated in the food chain little by little. When this toxin reaches a certain toxic limit, it kills creatures and devastates the natural world (Carson, 1962).

Overall, eco-efficiency strategies are not the optimal approach for achieving sustainability. Design techniques in linear flow seek only to eliminate waste in the product's life cycle by less extraction, less waste and less pollution; but without the capacity to maintain or enhance the quality or productivity of materials through subsequent life systems (Braungart et al., 2006).

1.3. Cradle-to-Cradle Model

To truly achieve sustainability, the industry must reassess the processes of various industrial activities—changing the conventional one-way, linear flows of materials to a cyclic process (Miyatake, 1996). In "*Cradle to Cradle: Remaking the Way We Make Things*", McDonough and Braungart (2002) use a cherry tree as an example to show how a circular system works in nature. A cherry tree produces thousands of blossoms throughout its life. However, only a few of them germinate cherry, and most fall on to the ground. The blossoms that do not germinate return to the soil and become nutrients for the surrounding plants. Generally, a plant absorbs biological nutrients from the soil and produces food for its growth, and the nutrient is a waste or by-product from other species. After the plant dies, the nutrients from the dead parts fall onto the ground and will then be decomposed by microorganisms and used as nutrients by other species. Therefore, the nutrients flow continuously in a cycle along with the life span of the plant. This example from nature is known as biological metabolism (Altman, and Dittmer, 1968). Eventually, nothing in nature will go to waste.

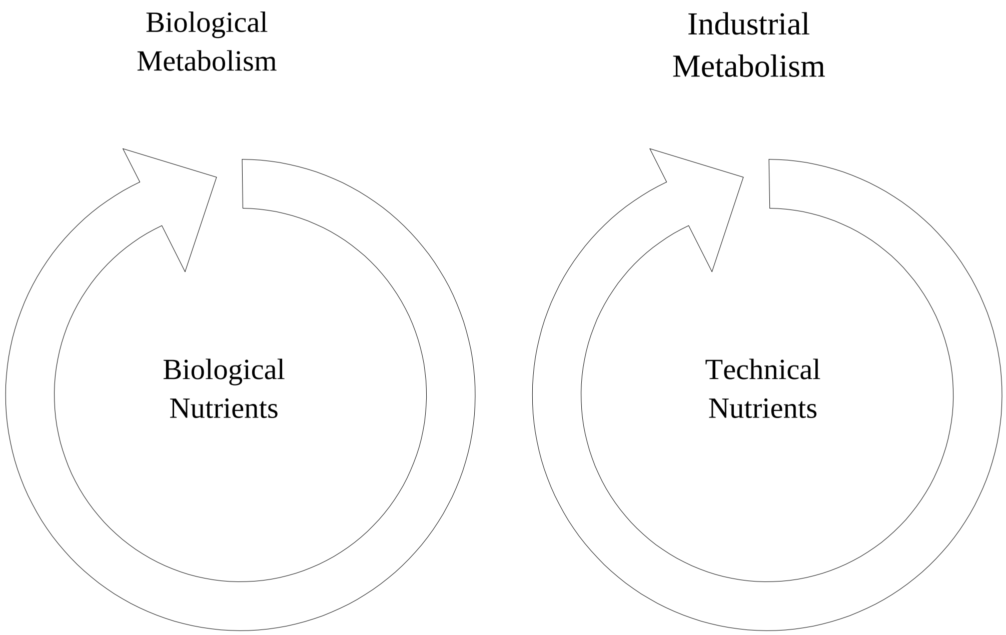

Figure 1.3: Cradle-to-Cradle Model (Source: McDonough and Braungart, 2002)

Ayres and Simonis (1994) pointed out the similarities between biological organisms and industrial activities on multiple levels. The cradle-to-cradle design uses biological metabolism as a reference to design cyclic industrial activities or processes, which is called industrial metabolism. Industrial metabolism assumes that materials do not have an end in life, and could be metabolized like biological nutrients in the plant's life span (Tischner and Charter, 2001). Figure 1.3 shows the similarities between biological metabolism and industrial metabolism processes: they are cyclic processes in which materials are turned back as nutrients. In nature, the materials or products that are designed in the biological metabolism system are called biological nutrients. They are eventually decomposed by microorganisms or absorbed by plants (e.g. plant-based or biodegradable materials). For industrial activities, materials or products recycled in the industrial metabolism system are called technical nutrients. They will go back into the industrial cycle they came from.

1.3.1. Eco-Effectiveness

The design concept for the cradle-to-cradle model is called “eco-effectiveness”. Eco-effectiveness aims to provide a practical design framework for creating products in a positive relationship with environmental health, economic growth and social development (Braungart et al., 2006). Compared to “efficiency”, which is defined as “doing less bad things”, “effectiveness” means “doing the right things” (Drucker, 2002). The key design principles of the cradle-to-cradle model are:

1. To equalize waste as food;
2. Use current solar income;
3. Diversify materials and resources use to enhance sustainability (McDonough and Braungart, 2002).

Eco-effectiveness changes industrial processes by regenerating previously depleted materials into useful and valuable materials (Tischner and Charter, 2001). Recycling is a process that a product at the end of its useful life is taken and turned into a usable raw material to make another product (Cameron, 2003), and by reuse, products are utilized for their original or a similar usefulness. Therefore, by intensifying the reuse and recycling processes, industry becomes less dependent on raw materials, and the value of materials is designed to be upgraded or maintained. The recycling and reuse industry has developed very fast over past few decades in all industrial activities, and more and more post-consumer products are sent back to a new life cycle by reusing or recycling. For example, in 2007, the amount of recycled MSW (municipal solid wastes) increased to 63.3 million tons, and the percentage of recycling increased from 16.7 percent in 1985 to 33.4 percent in 2007 (EPA, 2007).

Eco-effectiveness also designs materials flowing within different products' life cycles, because using materials in another product's cycle may be more efficient than sending it back to its own cycle (Kibert, 2008). Through continuously flowing within various cycles, "wastes" generated from one product's life cycle will be used in the next product's life cycle as "nutrients". Such design strategies have already been used in our industry. For example, steam generated by electrical power station during the manufacturing process is delivered to a new cycle such as oil refinery or bio-plant, because it is more efficient to be used in oil refinery or bio-plant than to produce electricity (Kibert, 2008).

Figure 1.4 shows the relationship between eco-efficiency and eco-effectiveness. Eco-efficiency is a process that the value of a material decreases along with its product's life cycle. In the long-term perspective, the eco-efficiency designs for less waste at a smaller negative consequence to environment, and the waste will be accumulated and the resources will be exhausted. In contrast, eco-effectiveness is capable of maintaining or upgrading the value of the materials by reusing and recycling post-consumer products or designing “waste” flowing into different products’ life cycles as “nutrients”. Overall, to achieve sustainability, industry has to change the eco-efficiency design to the eco-effectiveness design and thereby apply the cradle-to-cradle model (Braungart et al., 2006).

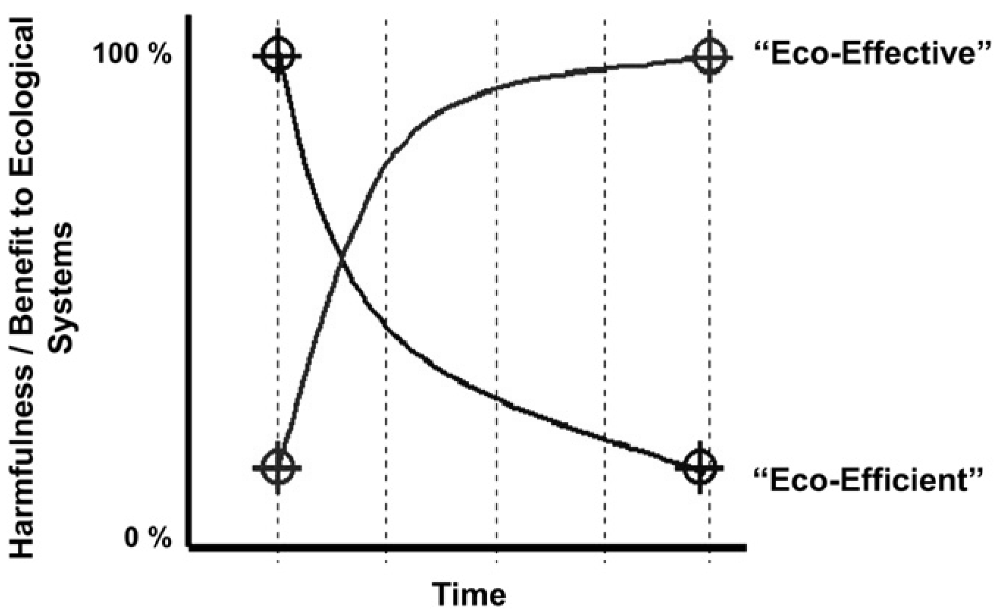

Figure 1.4: The Eco-Effectiveness Development (Source: Braungart et al., 2006)

1.4. Cradle-to-Grave Model vs. Cradle-to-Cradle Model in the Construction Industry

Construction industry plays an important role for our environment in sustainable design by reducing energy and resource use (Boyle, 2005; Head, 2003; Hendrickson and Horvath, 2000), as it consumes plenty of raw materials and generates huge amounts of waste each year (Bossink, 2002; Poon et al., 2004). In the United States, the building construction industry consumes about 40 percent of energy and accounts for 39 percent of carbon dioxide emissions annually (U.S. Green Building Council, 2007). Many countries had developed various “green” standards to achieve sustainability in this industry, such as the Building Research Establishment Environmental Assessment Method in the UK (BREEAM, 2008), the Comprehensive Assessment System for Building Environmental Efficiency in Japan (CASBEE, 2008), the Green Star in Australia (GBCA, 2008), and the U.S Green Building Council’s Leadership in Energy and Environment Design (LEED) (U.S. Green Building Council, 2009).

In the U.S, the USGBC represents every sector of sustainability in the building construction industry, and its LEED rating systems intends to apply sustainable design concepts to their program by implementing the five major areas of design principle: Sustainable Site, Water Efficiency, Energy and Atmosphere, Materials and Resources, and Indoor Environmental Quality (U.S. Green Building Council, 2005).

All those design principles aim to design for sustainability and reduce the reliance on resources through:

1. Managing, reducing, recycling and reusing of wastes;
2. Using environmentally preferable products and eliminate impacts on the environment;
3. Enhancing interaction between humans and the natural world;
4. Optimizing site potential;
5. Maximizing renewable energy use;
6. Conserving materials, energy, and water;
7. Enhancing indoor environment quality, etc (U.S. Green Building Council, 2005).

The USGBC and LEED rating system have profound effects in the building construction industry. By mid-year of 2006, about 400 buildings had been certified under LEED for New Construction (LEED-NC), and more than 2,600 buildings were undergoing certification in the United States (U.S. Green Building Council, 2008). Several other rating systems also have large influences on promoting the sustainable design for buildings, such as LEED for Existing Buildings (LEED-EB), LEED for Commercial Interiors (LEED-CI), LEED for Core and Shell (LEED-CS) and LEED for Schools (U.S. Green Building Council, 2009). Although other building assessment standards have been developed and implemented, LEED had been widely accepted as the standard for sustainable building, and recognized or adopted by other countries, such as Spain, Canada and China (U.S. Green Building Council, 2009).

However, the sustainable design in most green building systems still do not completely conform with the cradle-to-cradle concept, although many efforts have been put into practice to achieve sustainability with the guidance of LEED (Haggar, 2007). One reason is that the complex relationships between industrial activities and different stakeholders make it difficult to implement the sustainable design strategies (Savitz, 2006). For example, none of the LEED rating systems requires designers to determine the reusability and recyclability of materials at the design stage. Designers would not think about the deconstruction phase of the end of the materials or products they use in a building. The reuse and recycling of materials are still the responsibility of the contractors, manufacturers, and end users. Moreover, the current knowledge makes implementing the cradle-to-cradle model in construction industry difficult. First, tracking how materials flow along with a product's life cycle can be very hard. Current sustainability accounting methods, such as the Economic-Input-Output, and Life-Cycle Analysis need accurate and reliable information to measure the material-flow accurately (Hermreck and Chong, 2009). Second, it is hard to predict reliable energy consumption (also known as embodied energy) in the products life span (Australia State of the Environment Committee, 2001). As such, many questions exist: What are the materials consumed in a product's life cycle? What is the waste generated along the life cycle? How does the embodied energy influence the cradle-to-cradle design? And how far does construction industry to go to achieve the cradle-to-cradle model?

1.5. Resource Loop

To resolve those questions regarding implementing the cradle-to-cradle model, it is necessary for the building construction industry to have an intermediate model, which is named “resource loop”. The resource loop is an accounting model used to material and energy flow and thereby align the cradle-to-grave model with the cradle-to-cradle model (Steffen, 2006, Michelson, 2007). First, this model should be a “closed loop” system. In the Business Dictionary, “closed loop” is defined as a production system in which the wastes or by-product of one process are used in making another product (Business Dictionary, 2008). According to this definition, in a closed loop, wastes or by-product are designed to flow consistently within different products’ life spans after ending their initial functions. For example, waste paper is recycled to produce new paper; old office chairs are reused again in new offices, and fly ash from the combustion of coal is used in concrete. Second, a resource loop model should be capable of allowing designers to pool materials, energy and sustainable knowledge together to foster an understanding of how materials flow in or out of the product’s life cycle, and how embodied energy affects the effectiveness of sustainable design.

The material and energy are the two basic elements of a resource loop. “Closed loop” implies that the material flows as element in a continuous and circular system

(Hausman, 2004). The material-flow within the resource loop indicates the stages of a product's life cycle (e.g. extracting, manufacturing, maintenance, etc.), and the relationship between different life cycles are connected by material-flow. Energy in the resource loop plays a role that drives materials that flow through different stages. Energy is consumed when materials flow in or flow out of the resource loop, and transport materials from one stage to another stage. Given proper consideration on embodied energy and material-flow, a resource loop could be accomplished. Within the loop, materials and energy, which flow out of the resource loop, are "leaks" of the loop, and, those that flow into the source loop are "feeds".

Overall, resource loop is an accounting model which tracks material-flow and energy consumption, thereby identifies "leaks" and "feeds" of each stage. All activities of a product's life cycle are cooperated in its life span. It is necessary to notice that there are a few similarities between resource loop and supply chain. They both involve in material and energy flow, as well as multiple activities. However, their differences are significant. A supply chain is the alignment of firms that bring products or services to market (Lambert et al., 2004), but a resource loop considers all stages of products or service comprehensively.

1.5.1. Material-Flow

The first step for constructing a resource loop is to understand the life cycle of a product, as well as the events that actually occur during the life span, such as, what stages does a product have in its life span and how each material flows along with a product's life cycle. At each stage, there are always materials flowing in or flow out of products' life cycles. Materials could be chemicals, raw materials, fossil fuels, or minerals. During a product's life span, a certain quantity of the materials is often wasted during the manufacturing process, and some quantity of materials has to be fed back into the system during production (as post-industrial reuse), and maintenance (consumers maintaining the quality of the products). Once a product completes its function, some of materials will be disposed of as waste, and others will be reused or recycled as "nutrients" (i.e. its original form). The eco-effectiveness concept emphasizes the interdependence and integration of the life cycles of many materials (McDonough and Braungart, 2002). Therefore, tracking of material-flow will help designers better understand the overall impacts of different materials and products.

1.5.2. Embodied Energy

Embodied energy is the energy consumed in all activities necessary to support a process (Baird and Chan, 1983). Those activities include mining, manufacturing of materials and equipment, transport and administrative functions (Australia State of the Environment Committee, 2001). Energy is as important as materials in the resource loop. Christopher Hermreck and Wai K. Chong(2009) calculated embodied energy resulting from transportation, and showed that transportation of Construction and Demolition Waste (CDW) generates a significant amount of environmental footprints, and the transport energy may play a significant role in the total amount of embodied energy (Hermreck and Chong, 2009).

Each type of material consumes different categories and amounts of embodied energy in its whole life cycle (Thompson and Sorving, 2000). Depending on the specific project requirement and life cycle analysis (LCA) study, embodied energy may be broken down into the following categories (SETAC-Europe, 2003), as shown in Table 1.1:

Table 1.1: Embodied Energy Category, by End Use (Source: SETAC-Europe, 2003)

Energy Category	End of use
Electricity (delivered)	Electricity as measured by end user
Energy losses in electricity production	Loss in fuel conversion at power plants
	Transmission and distribution losses
Fuel extraction, processing and delivery	Energy consumption delivering fuel for use in power plants, transport equipment and industrial plants
Process heat	Fuel combusted in for its heat value but not for electricity generation
Transport	Fuel used in transport equipment
Feedstock	Fuel used in situations where they are not directly oxidized, such as oil and gas in plastics, carbon in cokes and pitch, and so on
Energy in capital	Energy use in capital equipment
Primary Energy	Energy use in manufacturing process

The background research indicates that: by applying cradle-to-cradle model, the industry will truly achieve sustainability. In construction industry, even though efforts have been put on sustainable design, many obstacles exist when implementing cradle-to-cradle model, such as, the complex relationships between different stakeholders; accounting methodologies for materials and energy. Since it is very difficult to replace cradle-to-grave with cradle-to-cradle completely under current situation, and both two models integrate energy and materials in different processes, resource loop is used to represent both the cradle-to-grave and cradle-to-cradle model via accounting materials and energy in products' life cycle. However, the current knowledge cannot provide a methodology for developing the resource loop; moreover, identifying the barriers of implementing cradle-to-cradle model in the industry is extremely hard. Therefore, this thesis will use a case study to show the development processes of resource loop and quantify the barriers by accounting all "leaks" and "feeds" in the loop.

Chapter 2 Research Objectives, Analysis Methodologies, and Scope

The eco-efficiency and cradle-to-grave model, which are established on the assumption of the model of one-way, linear flow of materials, aim to reduce the reliance on resources (such as materials and energy) and the negative consequence (such as waste, pollution and green house gas) to environment in a product's life cycle. However, designers do not consider the usefulness of materials of the product after it ends its life cycle. Eco-effectiveness and cradle-to-cradle design present an alternative design strategy by introducing recycled or reused materials as "nutrients". Thus, post-industrial and post-consumer materials will be fed back into the consumption and production processes as nutrients. This concept sounds ideal, but as discussed before, based on the current industrial model, it may be difficult to achieve the cradle-to-cradle model without the proper understanding of how materials perform during their product's life span.

2.1. Research Objectives

This thesis sets out a framework, which intends to resolve the major problems for implementing the cradle-to-cradle model—that is, to develop a resource loop representing both the cradle-to-grave and the cradle-to-cradle models. This loop will allow future researchers to better understand what "leaks" and "feeds" exist in the resource loop of a product. "Leaks", as mentioned before, is waste or by-product generated during the production or consumption process, and embodied energy. "Feeds" in a product's life cycle, include all materials used to manufacture, maintain, replace and discard the product. The leaks and feeds are often not documented properly due to the limitation in design; thus, the resource loop is used to account them in order to better reflect the resource-flow in the loop. In addition, from the process of developing the resource loop, it is easy to find out the barriers of converting cradle-to-grave model to cradle-to-cradle model, thus provide suggestions for future research in cradle-to-cradle design.

In order to better present the developing procedure, a case study is developed by tracking the life cycle of construction steel products. Construction steel products are the steel products used in construction industry. There are multiple reasons to choose construction steel as this case study objective. First, from the material's perspective, steel is a type of material, which has a wide range of applications because of its desirable characteristics of strength, durability and stability (AISE, 1998). The annual demand and consumption of steel keep increasing annually, surpassing the growth rate of other materials (MEPS LTD, 2008). It is reported that the estimated global consumption of steel products in 2004 is 941.5 million tons, about 8.5 percent above earlier year (MEPS LTD, 2008).

Second, steel recycling industry has been recycled steel for more than 150 years (EPA, 2009); thus, a lot of information, which is critical to develop the resource loop, such as recycling and reuse rate and embodied energy consumption, is already available.

The initial reason for steel recycling is that it was much cheaper to recycle steel than to mine for iron ore and manufacture it into steel and steel does not lose any of its inherent physical properties during the recycling process (Burgan and Sansom, 2006). More and more steel is now being recycled, as recycling will save many raw materials, energy consumption, and reduce the negative impacts on the environment. For example, recycling one ton of steel saves 1100 kg of iron ore, 630 kg of coal, and 55 kg of limestone (MobileOrganics, 2009). By recycling steel, the steel industry claim that it is able to reduce the energy intensity/ton of steel by 29 percent since 1990; green house gas/ton of steel shipped has been reduced by nearly 45 percent since 1975, and air and water emissions are 90 percent lower today than 10 years ago (Woods, 2008). More steel is recycled annually than all other materials. By August 24, 2007, the world's steel recycling rate is around 69 percent. The automotive industry has the highest steel recycling rates, at about 103.8 percent; then is construction industry, about 97.5 percent (Steel Recycling Institute, 2007).

Third, from the industrial perspective, steel can better contribute to sustainable design (Burgan and Sansom, 2006). Construction industry consumes 20 percent of all steel produced (American Iron and Steel Institute, 2006). In the U.S, it is estimated that in 2006, approximately 4 million tons of steel went into building construction worldwide (Baddoo, 2007). Sustainability strategies launched by public organizations, such as LEED rating system, also give many credits to steel due to its recyclability

(Sansom, 2003). For example, in LEED NC 2.2, Materials and Resources (M&R) Credit 3 and Credit 4 document the reuse and recycling materials, respectively, as well as M&R Credit 5 documents information for calculating transport energy. Overall, tracking the material-flow and embodied energy consumption, closing the resource loop, as well as identifying “leaks” and “feeds” within the loop for construction steel products are easier than other materials. Overall, the objectives of this thesis are to:

1. Understand the life cycle of construction steel products and track the leaks and feeds throughout the product’s life cycle;
2. Develop a methodology to develop the resource loop so that professionals can apply the method to develop various resource loops for accounting different products;
3. Determine the barriers of implementing the cradle-to-cradle model in an industrial system from the case study.

2.2. Research Analysis Methodologies

This thesis will:

1. Understand the principles and implementation limitations of the cradle-to-cradle model;
2. Develop a case study to show the procedures to develop a resource loop for the cradle-to-cradle ;

3. Develop the resource loop based on existing industry documented data by using steel as an example to track materials and energy flows.

2.3. Research Scope

Sustainable design is important to the construction industry, and the construction industry initiated many efforts to achieve sustainability. For example, construction steel is a highly reused and recycled product, and various agencies, such as the Steel Recycling Institute, International Iron and Steel Institute, and EPA, document the use of materials and energy, as well as the waste generated throughout the steel's life cycle. However, accounting of environmental and social impact is not tracked properly. As such, construction steel is one of the best materials to track, because it will provide a clear picture of how the "leaks" and "feeds" flow throughout its life cycle, thereby identify environmental and social impact. Therefore, the research scope is defined as follows:

1. The whole life cycle stages of construction steel products, such as "Construction Steel Product Manufacturing", "Construction", " Maintenance and Replacement", "Deconstruction", and "Recycling and Reuse" processes;
2. Material use in the life cycle of construction steel products, such as raw materials and chemicals;
3. The reuse and recycling rate, as well as demolition/deconstruction rate;

4. Embodied energy of steel products, such as feed stock energy, primary energy, and transport energy.

The acquired data for the scopes are classified into two categories: primary and secondary data:

1. Primary data are those obtained directly from specific facilities, such as LEED project spreadsheets and data from experienced industry professionals;
2. Secondary data are those obtained from published resources, such as the Steel Recycling Institute, the U.S. Geological Survey, and other reliable pubhlished literatures.

Chapter 3 Models for Resource Loop

In this chapter, a proposed preliminary resource loop is developed (Figure 3.1). It is a general model regardless of materials. Most materials follow a one-way, linear material-flow (Braungart et al, 2006), but materials are able to flow from linear one-way approach to a loop by intensifying the recycling procedure. Since the resource loop is capable of representing both cradle-to-grave and cradle-to-cradle model, it has characteristics of both models: resources flow in or out of the loop, but overall, waste becomes food. In addition, the resource loop can be used to provide a detail picture of the environmental and social impacts of products or materials. In a product's life span, material and energy are two basic elements that should be used to construct its resource loop as they contribute directly to both environmental and social impacts. The energy drives materials flow with different life stages of a product. In each stage, materials flow out of the loop and energy are consumed, resulting in "leaks"; or materials flow into the loop, resulting in "feeds". Figure 3.1 shows different life stages, leaks and feeds at stages in a closed loop of a product. Within the loop, the dashed line indicates material-flow, and the arrows indicate the flow direction. Along with the material-flow, the resource loop is divided into several stages, such as manufacture, product assembly, customer use, reuse and recycle. Energy is consumed to drive materials to flow within the loop. At each stage of the life cycle, there are feeds going in or leaks going out of the loop. At the final stage, recycling and reuse facilities send waste back into the loop; thus, "waste" are fed back to the loop as "food".

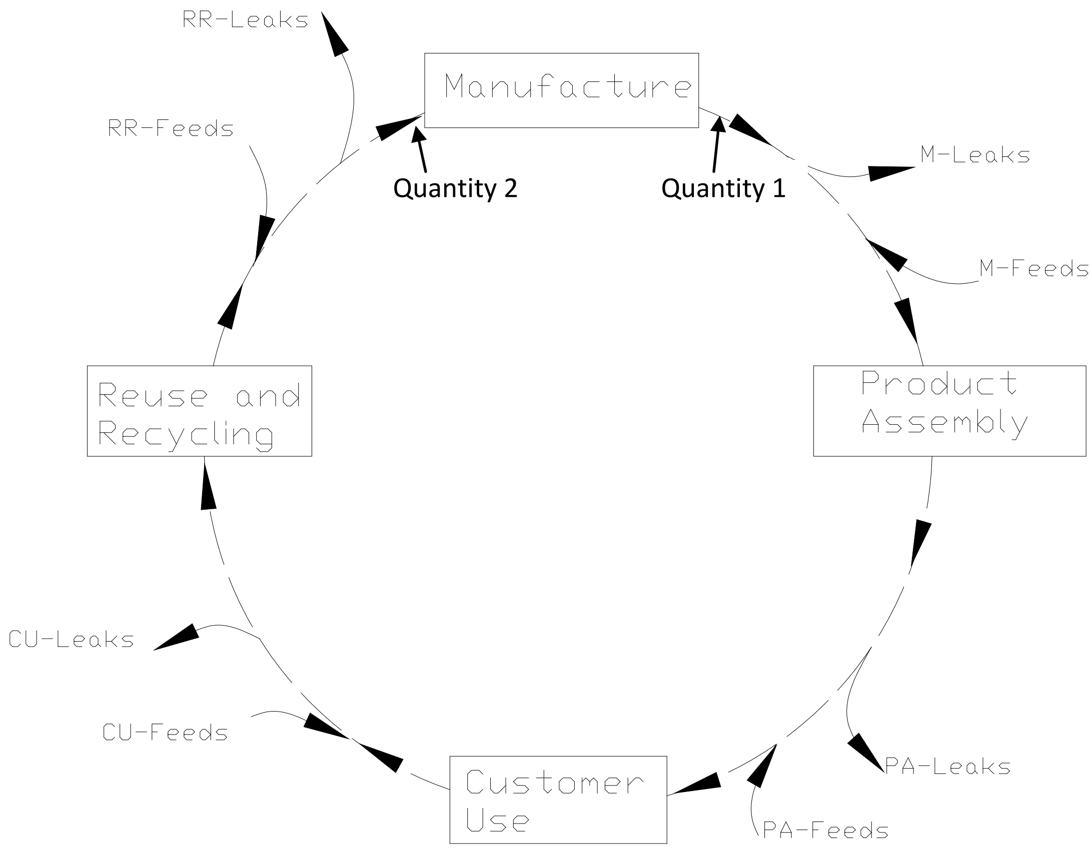

Figure 3.1: A Proposed Preliminary Resource Loop

Tracking material-flow and energy consumption, Eq. 3.1, Eq. 3.2, Eq. 3.3 and Eq. 3.4 are developed to quantify the relationship of “leaks” and “feeds” over the product’s life span. Among those equation, the total leaks (life cycle leaks) is defined as the sum of “leaks” in each stage, calculated by the following equation (Eq. 3.1)

$$\mathbf{LCL= M_l + PA_l + C_l + R\&R_l} \quad \text{(Eq. 3.1)}$$

Where, 'LCL' is the life cycle leaks, 'M_l', 'PA_l', 'C_l', and '$R\&R_l$' are leaks of manufacturing, product assembly, customer use, as well as the reuse and recycling processes, respectively. In addition, the total feeds (life cycle feeds) is defined as the sum of "feeds" in each stage, shown as the following formula (Eq. 3.2).

$$\mathbf{LCF= M_f + PA_f + C_f + R\&R_f} \quad \text{(Eq. 3.2)}$$

Where, 'LCF' is the life cycle feeds, 'M_f', 'PA_f', 'C_f', and '$RandR_f$' are feeds of manufacturing, product assembly, customer use, as well as the reuse and recycling processes, respectively.

The quantity of a product at certain stage is determined by the resources flowing in or out of its stages before this stage. Therefore, the quantity of product at a stage is the sum of all "leaks" and "feeds" happened before (Eq. 3.3). Take the preliminary resource loop as an example: the quantity of product at the customer use is the sum of M-Leak, PA-Leak, M-Feed and PA-Feed. It is necessary to notice that, in a product's life cycle, the amount of "leaks" is negative because they flow out of product's life cycle, and the "feeds" maintain positive.

$$\textbf{Quantity of product} = \sum_{i=1}^{n} \textbf{Feeds} + \sum_{i=1}^{n} \textbf{Leaks} \qquad \text{(Eq. 3.3)}$$

To evaluate how far a resource loop to go to achieve the cradle-to-cradle model, the major task is to evaluate how much "waste" is fed back to the beginning stage of the product as "food". Therefore, a coefficient will be used to quantify the ratio of waste turning to food. The coefficient is calculated by Eq. 3.4,

$$\mathbf{a} = \frac{\textbf{Quantity of product flowing into the beginning stage}}{\textbf{Quantity of product flowing out of the beginning stage}} \qquad \text{(Eq. 3.4)}$$

Where, the "quantity of product flowing into the beginning stage" (shown as quantity 2 in Fig. 3.1) is the amount of waste flowing back to a new life span after finish its own life span, also is the result after considering all the "leaks" and "feeds" in previous stages. The "quantity of product flowing out of the beginning stage" (shown as quantity 1 in Fig 3.2) is the amount of new product, which only passes through the manufacture stage. Therefore, 'a' stands for the percentage of waste becoming food.

Obviously, in the cradle-to-grave model, there is waste generated. Not all the waste will be fed back to the manufacture process, therefore, $0 \leq$ 'a' < 1; in the ideal cradle-to-cradle model, waste is fed back to new life span, thus 'a' = 1. In addition, the Cradle to Grave model has dominated the industrial system since the late-nineteenth century (Jones, 2008), and a large amount of leaks already became waste. Under such a circumstance, the design intends not only turn the leaks of current product's life span into feed, but also wastes generated in the past become nutrients, thus, 'a' > 1.

The meaning of identifying 'a' is significant. First, the value of 'a' indicates which model the product's life cycle is. If it is a cradle-to-grave model, the value of 'a' will show how far the resource loop is from cradle-to-cradle model. The more 'a' is close to zero, the less waste is turned to useful materials. Therefore, the coefficient could be used as an index for designers to choose more environmental-friendly products or evaluate how sustainable design for a product is.

It is important to notice that: each product has its own resource loop. For example, in the building construction industry, some products may have six stages, such as "extraction", "manufacture", "construction", "maintenance", "deconstruction", and "recycling and reuse". Therefore, the form of Figure 3.1 could be changed in different cases, as well as Eq. 3.1, Eq. 3.2, Eq. 3.3 and Eq. 3.4.

Chapter 4 Fitting Case Study into Resource Loop

The case study is going to adopt construction steel—a widely used product in construction industry as an example to pool a steel resource loop in practice. Each product has its own resource loop, and is different from others because of the various material-flows in the loop. However, the methodologies to identify the feeds and leaks of the loop, to close the resource loop are very similar. Thus, this thesis will only develop a typical resource loop that could potentially be used to develop the resource loop of other materials.

To develop a construction steel resource loop, it is necessary to take a close look at the life cycle of construction steel products. Figure 4.1 maps out many processes that exist during the construction steel's life cycle (Sansom and Meijer, 2001). Raw materials (e.g. ore and coal) are used to manufacture intermediate products, either through Basic Oxygen Furnace (BF/BOF) steel making route or Electric Arc Furnace (EAF) steel making route (Nijihawan, 1992). The intermediate products are fabricated for all kinds of construction steel products, such as Rebar, Wire Rod and BF Sections. New products are sent to the construction site and used in the construction process for a project. After project is finished, steel products will go through maintenance and replacement process because of function and aesthetics requirement. Due to deconstruction, steel is sorted and sent to reuse and recycling facilities. Then, some valuable products are used by new construction and maintain the same function, and this process is called reuse; the other valuable products are sent to the manufacturing process to produce new products, and this process is called recycling. The rest products are invaluable and discarded as waste. The arrows point out materials that flow from one stage to another stage.

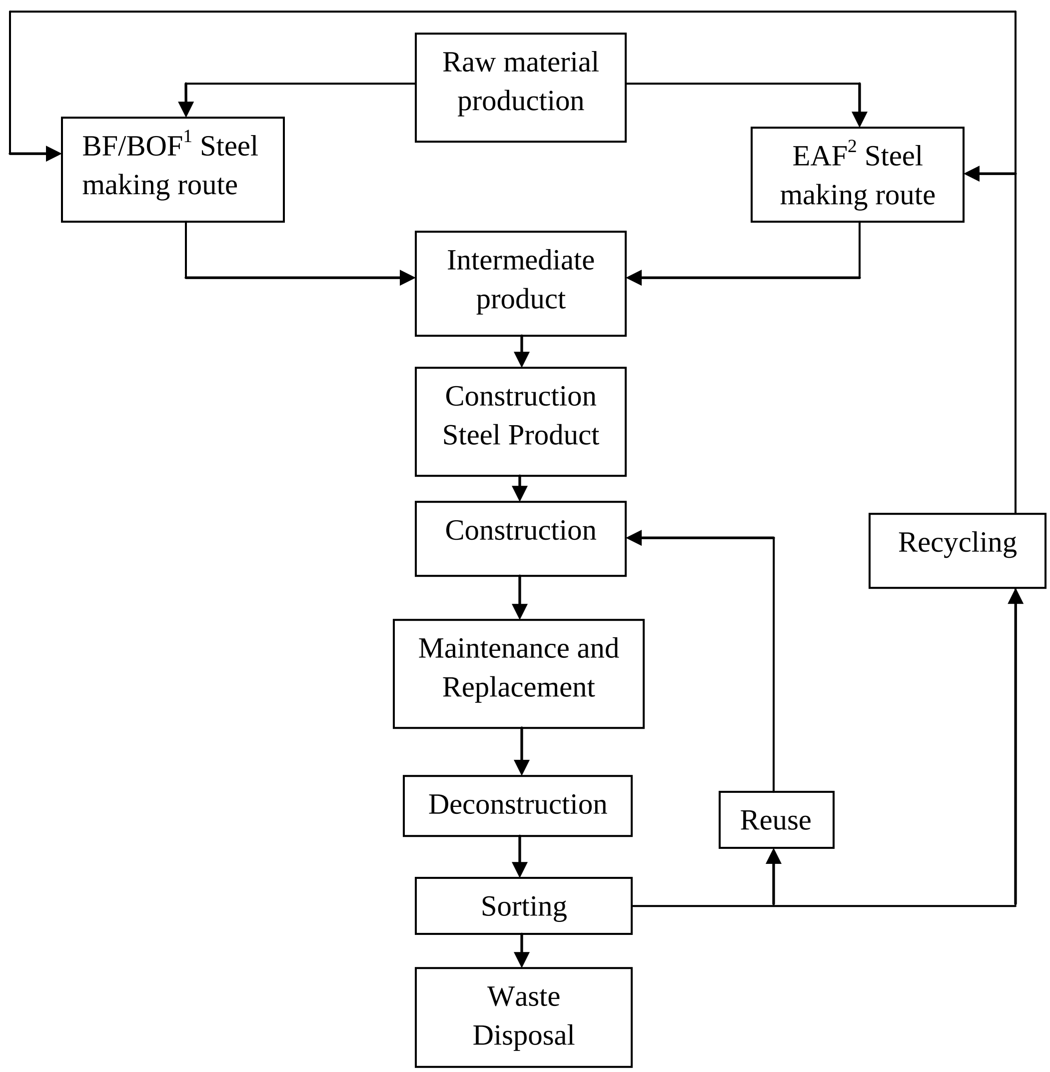

Figure 4.1: Typical Life Cycle of a Steel Construction Product
(Source: Sansom and Meijer, 2001)

(1). BF/BOF: Blast Furnace/Basic Oxygen Furnace
(2). EAF: Electric Arc Furnace

According to the Figure 4.1, the resource loop of steel construction products are divided into five important stages: Construction Steel Product Manufacturing, Construction, Maintenance and Replacement, Deconstruction, and Recycling and Reuse processes.

1. Stage 1, Construction Steel Product Manufacturing: there are two sub-stages: one is to use raw materials to produce the intermediate products, such as slab, coil and sheet; the other one is the production process of finished-steel construction products, such as structural steel, stainless steel, etc;
2. Stage 2, Construction Process: steel products are fixed and assembled for construction use;
3. Stage 3, Maintenance and Replacement: the maintenance process inspects, repairs and replaces the products in order to maintain the proper function;
4. Stage 4, Deconstruction Process: this process includes building demolition and deconstruction;
5. Stage 5: Recycling and Reuse Process: scraps and deconstruction wastes are sent here and refurbished so that they could be used in new projects and start new life cycle.

According to this thesis discussed before, “leaks” and “feeds” take place at every stage. To finish the resource loop, all the leaks and feeds need to be labeled. Through this case study, the following questions regarding construction steel resource loop are assessed: what are “leaks”, what are “feeds”, where do the leaks flow to, where the feeds come from, and how many are they?

For all stages, empirical information can be collected to fit into the loop. Some reasonable assumptions or basic calculation principles are made regarding the projects in order to simplify calculation, including:

1. Assumption 1: since the data for each stage come from different sources or projects, all the data are summarized based on the same unit, which is “1 kg of steel”. For example, the unit for material-based data is kg/kg, which means the kilograms of material that are added in or emitted in 1 kg of steel. For energy-based data, the unit is MJ/kg. However, during the calculation process, $/kg will be used to simplify the calculation; and convert to MJ/kg in the final report. Other different units will are specified later on in the thesis;
2. Assumption 2: “construction steel” is a vast subject. There are structural steel, weather steel, hot rolled, cold rolled, stainless steel, galvanizing, and so on. The amount of the same material or embodied energy consumption could be different because of the variety of steel types. This thesis will document the data according to the steel types in the projects, then, use the average data to represent the general steel products;

3. Assumption 3: data could be various at different years, but most have records in 2006. Therefore, most of date this thesis use is from 2006. When data in 2006 is not available, the latest data is used;
4. Assumption 4: at each calculation or analysis, main factors will be considerated, and the insignificant factors will be omitted. The numbers would not affect the analysis results as they are insignificant;
5. Assumption 5: the case study adopts construction steel products which are used in construction industry, but some data are about the overall steel products. To separate the construction part, it is necessary to have the ratio of construction steel and the overall steel products. According to American Iron and Steel Institute (2006) the construction steel products take around 19.13 percent of all distributed consumption, shown as Table 4.1. Therefore, this thesis will assume the construction product rate is 20 percent.

Table 4.1: Distribution of Shipment of Steel Mill Products, by Steel Market, 2006
(Source: American Iron and Steel Institute, 2006)

	Quantity	Percentage
	Thousand metric tons	%
Service centers and distributors	27,300	27.49
Construction	19,000	19.13
Automotive	14,100	14.20
Machinery	1,380	1.39
Containers	2,820	2.84
All others	34,700	34.94
Total	99,300	100

Chapter 5 Case Study Analysis

In this chapter, the thesis will take a close look at the material-flow and the embodied energy in the different stages of the steel products' life spans. Some data can be gotten directly by approaching agencies who documented them, such as inventory of all materials except steel products, primary energy consumption, steel products waste and consumption in maintenance stage, and recycling and reuse rate. Others can be calculated with related information, such as transport energy. A few equations will be developed and used in order to quantify the feeds and leaks within the resource loop of construction steel products, and they will be discussed in detail when using them. During the calculation process, all the assumptions listed in Chapter 4 will be adopted to simplify the calculation while ensuring the accuracy of analysis results.

5.1. Stage 1: Construction Steel Product Manufacturing

Steel is an alloy composed of iron and carbon. It consists mainly of iron, with a carbon content between 0.2 percent and 2.04 percent by weight (Fruehan, 1998). To control the qualities of the steel, such as the hardness, ductility and tensile strength, some elements in the ore have to be eliminated, for example, sulfur, nitrogen, and phosphorus make steel more brittle, so these commonly found elements must be removed from the ore during the steel manufacturing process (Fruehan, 1998). Various other elements are used, such as manganese, chromium, vanadium, and tungsten (Ashby and David, 1992). For example, nickel and manganese in steel add to its tensile strength and make austenite more chemically stable; chromium increases its hardness and the melting temperature. In addition, during the manufacturing process, many chemical reactions occur, and energy is either consumed or emitted to finish those reaction processes. For example, the two basic reactions of steel manufacturing process are shown below (Fruehan, 1998).

$C + O_2 = CO_2$ (+97,200 cal.) (Reaction 1)

$CO_2 + C = 2CO$ (- 68,040 cal.) (Reaction 2)

Where C is the carbon; O_2 is the oxygen; CO is the carbon monoxide; and CO_2 is the carbon dioxide. When hot coal is exposed to oxygen, reaction 1 immediately happens and 97,200 cal is given off (Fruehan, 1998). In the presence of an excess of coal at high temperature, CO_2 is reduce to CO, and 68,040 cal. are absorbed (Fruehan, 1998). Overall, manufacturing steel products is a completed process involved in multiple materials exchange and energy consumption. The added or eliminated materials and the primary energy are the main information need to be analyzed, which is organized and evaluated by the LCA tool to develop the life cycle inventory. However, transport energy is one of the important categories of energy not documented in the life cycle inventory. Thus, this thesis will calculate this part of energy independently.

5.1.1. Life Cycle Inventory for Construction Steel Products

Life cycle inventory is an accounting of the energy and waste associated with a product's life span through manufacture to disposal (Vigon, 1994). The International Iron and Steel Institute (IISI, 2008) provides the inventories for Rebar/Wire Rod, BF Sections and EAF Sections for this thesis (Table 5.1, Table 5.2, Table 5.3).

According to Assumption 1, all the data in the inventories are summarized based on 1 kg of steel products. Table 5.1 summarized the materials (inputs) used for manufacturing 1 kg of Rebar/Wire Rod, BF Sections, and EAF Sections, respectively; Table 5.2 is the wastes (outputs) for 1 kg of those types of steel; and Table 5.3 is the summary of energy consumption except for transport energy.

The life cycle inventories for construction steel products document materials use or waste within the products' life cycle. Therefore, the data in the inventories are net results. For example, there are several negative numbers, such as Zinc in Table 5.1 and Dioxins in Table 5.2. To Zinc, the negative number indicates that when steel is recycled Zinc is captured, and the amount of recycling is more than the amount added in. To Dioxins, the negative number indicates that when manufacturing steel, the amount of Dioxins added in is more than the amount that is emitted into the environment.

Table 5.1: Life Cycle Inventory Data for Construction Steel Products: Inputs
(Source: Steel Recycling Institute, 2008)

Major Articles	Units	Rebar/Wire Rod	BF Sections	EAF Sections Products
(r) Coal (in ground)	Kg	0.239	0.266	0.208
(r) Dolomite ($CaCO_3.MgCO_3$, in ground)	Kg	0.023	0.029	0.017
(r) Iron (Fe)	Kg	0.361	0.321	0.443
(r) Limestone ($CaCO_3$, in ground)	Kg	0.112	0.129	0.065
(r) Natural Gas (in ground)	Kg	0.034	0.069	0.050
(r) Oil (in ground)	Kg	0.044	0.064	0.022
(r) Zinc (Zn)	Kg	-0.003	-0.003	-0.006
Water Used (total)	Liter	1.057	1.598	3.834

(r): Raw material in ground

Table 5.2: Life Cycle Inventory Data for Construction Steel Products: Outputs
(Source: Steel Recycling Institute, 2008)

Major Articles	Units	Rebar/Wire Rod	BF Sections	EAF Sections Products
(a) Cadmium (Cd)	g	5.425×10^{-5}	6.688×10^{-5}	6.420×10^{-5}
(a) Carbon Dioxide (CO_2)	g	873.122	1,060.763	889.907
(a) Carbon Monoxide (CO)	g	10.4078	12.223	10.827
(a) Chromium (Total)	g	3.897×10^{-4}	1.191×10^{-4}	1.368×10^{-4}
(a) Dioxins (unspecified, as TEq)	g	-6.165×10^{-9}	-6.663×10^{-10}	6.442×10^{-9}
(a) Hydrogen Chloride (HCl)	g	0.048	0.054	0.023
(a) Hydrogen Sulphide (H_2S)	g	0.033	0.031	0.022
(a) Lead (Pb)	g	1.963×10^{-3}	2.386×10^{-3}	2.261×10^{-3}
(a) Mercury (Hg)	g	1.174×10^{-4}	1.325×10^{-4}	9.186×10^{-5}
(a) Methane (CH_4)	g	0.604	0.907	0.598
(a) Nitrogen Oxides (NOx as NO_2)	g	0.936	1.842	1.304
(a) Nitrous Oxide (N_2O)	g	0.028	0.045	0.038
(a) Particulates (Total)	g	0.580	0.217	0.775

Table 5.2: Life Cycle Inventory Data for Construction Steel Products: Outputs (continued)

Major Articles	Units	Rebar/Wire Rod	BF Sections	EAF Sections Products
(a) Sulphur Oxides (SOx as SO_2)	g	1.983	3.117	0.884
(a) VOC (except methane)	g	0.164	0.100	0.161
(a) Zinc (Zn)	g	0.017	0.016	0.013
(w) Ammonia (NH^{4+}, NH_3, as N)	g	0.061	0.272	0.043
(w) Cadmium (Cd^{2+})	g	6.629×10^{-6}	-4.430×10^{-6}	8.735×10^{-6}
(w) Chromium (Total)	g	9.486×10^{-5}	7.781×10^{-5}	1.237×10^{-5}
(w) COD (Chemical Oxygen Demand)	g	-0.023	0.018	0.043
(w) Iron (Fe^{2+}, Fe^{3+})	g	0.066	0.187	0.055
(w) Lead (Pb^{2+}, Pb^{4+})	g	4.168×10^{-4}	2.884×10^{-4}	1.050×10^{-4}
(w) Nickel (Ni^{2+}, Ni^{3+})	g	5.663×10^{-5}	4.264×10^{-5}	5.677×10^{-5}
(w) Nitrogenous Matter (unspecified, as N)	g	0.033	0.036	-0.001
(w) Phosphorous Matter (unspecified, as P)	g	2.520×10^{-3}	3.387×10^{-3}	2.497×10^{-3}

Table 5.2: Life Cycle Inventory Data for Construction Steel Products: Outputs (Continued)

Major Articles	Units	Rebar/Wire Rod	BF Sections	EAF Sections Products
(w) Suspended Matter (unspecified)	g	0.083	0.097	0.040
(w) Zinc (Zn^{2+})	g	2.347×10^{-5}	1.949×10^{-4}	2.565×10^{-5}
Non-allocated by-product (See Table Below)	Kg	0.019	0.056	0.039
Waste (total)	Kg	0.389	0.230	0.454

(a): Airborne emissions
(w): Waterborne emissions

Table 5.3: Life Cycle Inventory Data for Construction Steel Products: Energy Consumption (Source: Steel Recycling Institute, 2008)

Major Articles	Units	Rebar/Wire Rod	BF Sections	EAF Sections Products
Feedstock Energy	MJ	0.444	0.283	-0.272
Fuel Energy	MJ	12.623	16.247	13.808
Non Renewable Energy	MJ	11.539	14.789	11.591
Renewable Energy	MJ	1.163	1.446	1.627
Total Primary Energy	MJ	13.068	16.530	13.524

In Table 5.1, the first column lists the major raw materials used in the manufacturing process; the second column shows the units for those materials (Kg is kilogram); and the third, fourth and fifth columns show how many materials are used in order to manufacture 1 kg of those steel products. In Table 5.2, the first column lists the name of the wastes generated; the second column shows the units (g is gram); the third, fourth and fifth columns show how many wastes are emitted into the environment while making 1 kg of steel products. For example, 1 kg of rebar would consume 0.239 kg of coal, and would emit 5.43 g of cadmium. In Table 5.3, the first column shows the categories for embodied energy (the categories of embodied energy are classified in Table 1.1); the second column shows the units (MJ is million joule); the third, fourth, and fifth column indicates how much energy is consumed when producing 1 kg of steel products.

5.1.2. Embodied Transport Energy Calculation for Imports and Exports of Construction Steel Products

Transport energy is one of the most important categories of embodied energy (Hermreck and Chong, 2009), but it is not documented in most life cycle inventories. It should be calculated separately in each stage. This thesis will incorporate multiple calculation processes for the transport energy, and normally, the unit of energy use MJ (Mega Joule). However, some researchers use currency units (U.S. dollar) to evaluate energy consumption (Hermreck and Chong, 2009), because currency units can better reflect the economic impacts on sustainable design, and the stakeholders are more interested in the cost analysis (Chong et al., 2007). This thesis will get the final results using both MJ and USD. It is necessary to notice that if the energy unit is used in the calculation processes, the result of each calculation step will generate large numbers. This is because the number using the energy unit is much larger than the currency units for the same amount of energy. For example, the energy of 1 gallon of diesel fuel is 146.7 MJ (Annamalai and Puri, 2006), and the average cost per gallon of diesel fuel in the U.S. for the first quarter of 2008 was $2.71 (Yahoo Finance, 2008). Obviously, using costs in the calculation processes will be more convenient than using the energy unit. Therefore, this thesis will use the USD during the calculation processes, and in the end, convert the results from USD into MJ.

In general, the transport energy consumption is largely dependent on the amount of transport products, transportation distance, the type of the fuel and the fuel efficiency of the vehicle used to transport the products. At Stage 1, transport energy is consumed when transporting products from the manufacturing mills to the distributors. The transportation process could either be international or domestic. The U.S. imports and exports a large amount of steel products each year, and the international trading routes are far reaching. Compared to the international trading, the domestic trading is short by nature, thus the energy consumption for domestic trading is very small. According to Assumption 4, this thesis will use the energy consumption of the international trading to represent the total embodied transport energy of Stage 1.

The import/export amount data are provided by the American Iron and Steel Institute(AISI). Those data could be used to represent 100 percent of the raw steel products in the United States (AISI, 2008). According to the annual report of AISI, the raw steelmaking capacity of the United States was about 112 million metric tons (Mt); and the raw steel production was 98.2 Mt in 2006 (AISI, 2008). Table 5.4 lists the major international trading of steel imports and exports of the United States in 2006 (Assumption 4). The first column lists the name of the country which traded with the U.S.; the second and third columns list the amount of imported and exported steel products, represented by ‘a’ and ‘b’, respectively.

Table 5.4: U.S Imports and Exports of Steel Mill Products, by country[1, 2], 2006
(Source: American Iron and Steel Institute, 2008)

Country	2006	
	Imports (a)	Exports (b)
Argentina	148	3
Australia	1,060	13
Brazil	2,630	37
Canada	5,400	5,530
China	4,890	89
European Union[3]	5,690	348
Germany	1,220	43
Japan	1,910	23
Korea, Republic of	2,540	47
Mexico	3,300	2,000
Russia	3,300	--
South Africa	426	10
Sweden	255	4
Taiwan	1,700	16
Turkey	2,180	--

Table 5.4: U.S Imports and Exports of Steel Mill Products, by country, 2006 (Continued)

Country	2006	
	Imports (a)	Exports (b)
Ukraine	1,590	--
Venezuela	180	54
Other	2,670	603
Total	41,100	8,830

(--): Zero
(1): Thousand metric tons unless otherwise specified
(2): Data are rounded to no more than three significant digits; may not add to totals shown
(3): Excludes Germany and Sweden

To calculate the transport energy, the first step is to get the amount of transport products. Data in Table 5.4 is about all steel products; therefore, it is necessary convert to construction steel products by timing a construction product rate, representing by ‘c’. According to Assumption 5, ‘c’ is 20 percent, thus, the total amount of construction products can be calculated by the following equation (Eq. 5.1),

The amount of construction products = total amount of steel product × c

(Eq. 5.1)

Then, the transport distance is estimated. The type of the fuel and the fuel efficiency are used to calculate freight rate, which is the energy cost of the vehicle moving 1 mile. Therefore, the freight rate is result of amount of energy use for moving 1 mile multiplying the price of energy. For most international trading, the transport uses cargo ships, which use diesel fuel. The average cargo ship gets about 0.008 miles per gallon diesel (Pubdit, 2008) therefore, this thesis will assume the general fuel consumption for a cargo ship is 120 gallons of diesel fuel per mile, and the average cost per gallon of diesel fuel is $2.71/gallon (Yahoo Finance, 2008). Therefore,

Freight rate: i = 120 gallons/mile × $2.71/gallon= $325.2/mile

The last step is to determine the cargo ship size because ship size decides how many trips are needed to transport the products. This thesis will assume all the international trading uses Handymax or Surpramax, because these two types of ships represent 71 percent of all cargo ship over 10,000 metric tons of deadweight (DWT) (The Royal Institute of Naval Architects, 2005). Generally, modern Handymax designs are typically 52,000-58,000 DWT in size (The Royal Institute of Naval Architects, 2005), thus, ‘w’ is 55,000 DWT.

Overall, the calculation of embodied transport energy costs will use the following equation (Eq. 5.2),

The transport energy cost = import/export amount × distance × freight rate ÷ cargo ship size (Eq. 5.2)

Here is an example to calculate the embodied transport energy consumption for importing construction steel products from Argentina:

The total amount of imports is 29.6 thousand metric tons; the distance from Argentina and the United States is estimated at 5,450 miles; the freight rate is \$325.2/mile; and the bulk carrier capacity is 55,000 DWT, therefore,

$$m = (29.6 \times 10^3 \text{ metric tons} \times 5{,}450 \text{ miles} \times \$325.2/\text{mile}) / 55{,}000 \text{ DWT}$$

$$= \$954{,}000$$

Table 5.5 is developed to show the results of the embodied energy calculation for importing and exporting steel construction products. In the table, the first column shows the name of the country with which the U.S. has traded; the second column shows the estimated distance between those countries and the U.S., represented by ‘e’. The third and fourth columns show the calculated amount of construction steel imports and exports, represented by ‘j’ and ‘k’, respectively. ‘c’ in the third and fourth columns stands for the construction products rate. The fifth and six columns are the results of the transport energy costs for importing and exporting construction steel products from other countries, represented by ‘m’ and ‘n’, respectively; ‘i’ is the freight rate; ‘w’ is the cargo ship size.

Table 5.5: Embodied Energy Calculation for Imports and Exports, Construction

Country	Average Distance [1] (e)	2006		Embodied Energy	
		Imports j=a×c	Exports k=b×c	Imports m=j×e×i/w	Exports n=k×e×i/w
	Miles	Thousand Metric Tons	Thousand Metric Tons	Thousand USD	Thousand USD
Argentina	5,450	29.6	0.6	954	19
Australia	9,463	212	2.6	11,862	145
Brazil	4,273	526	7.4	13,289	187
Canada	1,523	1,080	1,106	9,726	9,960
China	7,215	978	17.8	41,722	759
European Union	4,700	1138	69.6	31,625	1,934
Germany	4,850	244	8.6	6,997	247
Japan	6,247	382	4.6	14,110	170
Korea, Republic of	6,543	508	9.4	19,653	364
Mexico	1,075	660	400	4,195	2,542
Russia	5,612	660	--	21,900	--
South Africa	9,037	85.2	2	4,553	107
Sweden	4,580	51	0.8	1,381	22

Table 5.5: Embodied Energy Calculation for Imports and Exports, Construction (Continued)

Country	Average Distance [1] (e)	2006		Embodied Energy	
		Imports j=a×c	Exports k=b×c	Imports m=j×e×i/w	Exports n=k×e×i/w
	Miles	Thousand Metric Tons	Thousand Metric Tons	Thousand USD	Thousand USD
Taiwan	7,537	340	3.2	15,152	143
Turkey	6,321	436	--	16,295	--
Ukraine	5,680	318	--	10,680	--
Venezuela	2,830	36	10.8	602	181
Other		534	120.6	N/A	N/A
Total		8,220	1,766	224,696	16,780

(--): Zero
(1): Distance is estimated by http://www.convertunits.com/distance

5.2. Construction Projects

For the Construction and Deconstruction Processes, this thesis will select four projects to analyze the material-flow and the embodied energy consumption. All of the selected projects are designed and constructed by incorporating sustainability concepts. Three of them are LEED certified, and achieved the LEED credits of Materials and Resources. Another one is in the LEED evaluation process. Project 1 is located in Las Vegas, NV, Project 2 is located in Eugene, OR; Project 3 and Project 4 are in Kansas City, MO. In the thesis, Project 1, 2, and 3 will be used to track the materials-flow from the Recycling and Reuse Process to the Construction Process, and Project 4 will provide a Waste Reduction Progress Report for the analyzing in the Deconstruction Process.

Table 5.6 shows the general information of the four projects.

Table 5.6: Projects Background

Project Name	Location	Building Types	Gross Floor Area	LEED Accredited	LEED Version
Project 1	Las Vegas, NV	Commercial	180 acres	Platinum	NC[1] v2.0/2.1
Project 2	Eugene, OR	Public order and safety	267,000 sq. feet	Gold	NC v2.0/2.1
Project 3	Kansas City, MO	Commercial	N/A	Tracking	N/A
Project 4	Kansas City, MO	K-12 education	315,000 sq. feet	Silver	NC v2.0/2.1

(1): LEED for New Construction and Major Renovations

Project 1 is a commercial building used for education and entertainment in Las Vegas, NV. After being certified in 2008, Project 1 became the largest Platinum LEED rated commercial building project in the southwest. Project 1 earned eight credits for Materials and Resources by adopting strategies of utilizing local and recycled materials.

Project 2 received LEED Gold in 2006. It is a public building located in Eugene, OR. The project extensively uses materials with recycled content—more than 20 percent of materials, by cost. Other Green strategies for Materials and Resources include:

design for reduction in materials use, use of post-industrial recycled materials, and preference for local resources and manufactured materials.

Project 3 is a commercial project in Kansas City, MO. It is expected to get the LEED Silver certification for its design strategies. The strategies for Materials and Resources in this project include: maximizing reuse and recycle materials, and decreasing the distance that the materials are manufactured from the site.

Project 4 is a K-12 education facility in Kansas City, MO. It received LEED Silver in 2008. The project selected materials based on the principal of durability, low maintenance requirements, recycled content, and proximity of the factory of production. In total, about 64.4 percent of the construction wastes were diverted from landfills.

Overall, these four projects are similar in maximizing reusing and recycling materials and minimizing consumption in embodied transport energy by shortening the distance of transportation products. During the LEED rating process, contractors have to develop LEED spreadsheet to document the data of products and resource consumption. With the help of LEED spreadsheets, these four projects are able to show their steel recycling rates, deconstruction rates and the transportation distance to the project sites from the steel mills or the recycling and reuse facilities.

5.3. Stage 2: Construction Process

In order to encourage construction industry use more building products that contain recycled content materials, thereby reducing the reliance on virgin materials, LEED NC 2.2 proposed MR credit 4. As discussed above, there are two types of waste generated during a product's life cycle: the post-consumer waste, which is a waste type by the end-consumer of a product(USGBC, 2006); the post-industrial waste, which is the waste generated during a product's manufacturing process (USGBC, 2006). Since the post-consumer waste is more heavily weighted than post-industrial waste because of their important environmental and social impacts, the equation (Eq. 5.3) used to calculate recycled content is defined in LEED NC 2.2, MR Credit 4, and has been widely accepted as criteria to quantify recycled content in construction project.

$$\textbf{Recycled content} = \textbf{product cost} \times \textbf{post-consumer percentage (\%)} + \textbf{0.5} \times \textbf{product cost} \times \textbf{post-industrial percentage (\%)} \qquad \text{(Eq. 5.3)}$$

The recycled content of construction steel products is the content manufactured by recycled steel. The calculation results of the recycled content indicate the percentage of recycled content in new products. Here is a calculation example of Eq. 5.3. In Project 1, Building 1, the material cost for Rebar is $1,311,512. According to the data in the LEED spreadsheets, the recycled materials from post-consumer content is 80%, and the percentage of post-industrial is 20%, therefore, the value of the recycled content is,

$1,311,512 × 80% + 0.5 × $1,311,512 × 20% =$1,180,361

The total recycled content for Rebar is,

$1,180,361÷ $1,311,512 = 90%

Calculating transport energy for construction process is similar to the procedures of the Stage 1. Therefore, the embodied transport energy calculation will use Eq. 5.2 as a reference, and the calculation equation (Eq. 5.4) is developed as,

The transport energy cost = total amount of steel products × distance

× freight rate ÷ truck capacity (Eq. 5.4)

Since the data in LEED spreadsheet is documented in price, the first step is to convert the costs, represented by 'f', to weight, represented by 'g'. The weight of steel products is equal to the total cost divided by unit price, shown as the following equation (Eq. 5.5). The unit price of steel products are various for each product and each year. According to the Assumption 3, this thesis will use the average price of construction steel products in 2008, which is \$956/ton (MEPS Steel Prices On-line, 2009).

Total amount of steel products (g) = product cost (f) ÷ product price

(Eq. 5.5)

"Distance" in Eq. 5.4 is documented in the spreadsheet of LEED NC 2.2, MR Credit 5: Regional Materials. There are two types of distances: the manufacturing location in miles from the project site, and the harvesting location in miles from the project. Energy is consumed for transporting products both from the manufacturing location to the project site and from the harvesting location to the project site.

The result for the total amount of steel products divided by truck capacity is the shift of transporting steel products, represented by 't'. The truck capacity ranges from 20 tons to 50 tons (Federal Highway Administration, 2007). This thesis will assume the truck capacity is 25 tons/shift. Therefore, the shift is calculated as the following equation (Eq. 5.6),

Shift (t) = total amount of steel products (g) ÷ truck capacity (Eq. 5.6)

The last parameter required for Eq. 5.4 is the freight rate. Researchers have found that the truck could drive about 2.55 km with 1 liter diesel (Hermreck and Chong, 2009).

In another way, it equals to 6 mile/gallon. As this thesis discussed before, the price of diesel fuel is $2.71/gallon. Therefore, the freight rate (i) is (Eq. 5.7),

Freight rate for truck: i = $2.71/gallon ÷ 6 mile/gallon = $0.452/mile (Eq. 5.7)

Therefore, Eq. 5.4 could be transformed into the following equation (Eq. 5.8),

The Transport Energy = distance from project × freight rate × shift (t)

(Eq. 5.8)

Here is an example of applying Eq. 5.8. In Project 1, Building 1, the total cost of Rebar in this project is $1,311,512, thus,

The shift (t) = $1,311,512 ÷ $956/ton ÷25 tons/shift = 54

The distance from the manufacturing location to the project is 10 miles, therefore,

The embodied transport energy cost = 10 miles × $0.452/mile × 54 = $243

Overall, there are two main factors that are required to be calculated in this stage. One is the recycled content for tracking the material-flow, which uses Eq. 5.3; the other is the transport energy consumption, which uses Eq. 5.8, but the calculation procedures will use equations from Eq. 5.5 to Eq. 5.7. The following sections will use three projects—four buildings in total (Projects 1 has two buildings) to track the leaks and feeds of steel products in the construction stage. The detail results of the calculation for each project will be shown in the tables.

5.3.1. Project 1: Las Vegas, NV

5.3.1.1.Building 1

Table 5.7 shows the calculation results for the recycled content in construction steel in Project 1, Building 1. According to the calculation results, the total material cost of Project 1, Building 1 is $4,296,218, and the total recycled content is $3,495,810. Therefore, the recycled materials used in this building is 81.37% of the total steel products

Table 5.7: Project 1, Building 1, Visitors Center: Recycled Content for Steel

Description of Product	Product Cost	MR Credit 4: Recycled Content			Recycled
		Post Consumer	Post Industrial	Value	
	$	%	%	$	%
Rebar	1,311,512	80%	20%	1,180,361	90%
Structural Steel-Tube	92,480	65%	35%	76,296	82.5%
Structural Steel-Angle	208,080	99%	1%	207,040	99.5%
Structural Steel-Wide Flange 1	1,202,240	80%	15%	1,051,360	87.5%
Structural Steel-Plate	809,200	50%	50%	606,300	75%
Misc Metal	63,000	0%	90%	28,250	45%
Steel Stud and Track	132,668	64%	25%	101,431	76.45%
Steel Perforated Panels	37,301	25%	35%	15,853	42.5%
Steel Angles	4,565	83%	0%	3,789	83%
Stainless Steel Sheets	21,906	72%	0%	15,772	72%

Table 5.7: Project 1, Building 1, Visitors Center: Recycled Content for Steel (continued)

Description of Product	Product Cost	MR Credit 4: Recycled Content			Recycled
		Post Consumer	Post Industrial	Value	
	$	%	%	$	%
Flattened Expanded Metal	2,364	0%	0%	0	0%
Galv. Perforated Panels	8,006	0%	0%	0	0%
Steel Bar	9,860	85%	15%	9071	92%
Structural Steel-Wide Flange 2	114,232	75%	10%	91,386	80%
Structural Steel	5,000	60%	40%	4,000	80%
Hollow Metal Door/Frame	28,043	25%	10%	8,415	30%
Metal Studs	241,214	20%	40%	96,486	40%
Metal Lockers	4,547	0%	0%	0	0%
Overall	4,296,218	N/A	N/A	3,495,810	81.37%

The results of transport energy for construction steel products in Project 1, Building 1 are listed in Table 5.8 and Table 5.9. In Table 5.8, the first column shows the name of products used in the Building 1; the second column shows the products cost (f); the third column shows the weight of products (g), which is calculated by Eq. 5.5; and the last column shows the calculated results of shift (t), according to Eq. 5.6.

Table 5.8: Project 1, Building 1, Visitors Center: Transportation Shift

Description of Products	Products Cost (f)	Products in Weight $g = f \div 956$	Shift $t = g \div 75$
	$	Tons	
Rebar	1,311,512	1,372	54
Structural Steel- Tube	92,480	97	4
Structural Steel- Angle	208,080	218	9
Structural Steel- Wide Flange 1	1,202,240	1,258	50
Structural Steel- Plate	809,200	846	34
Misc Metal	63,000	66	3
Steel Stud and Track	132,668	139	6
Steel Perforated Panels	37,301	39	2
Steel Angles	4,565	4.8	(1)
Stainless Steel Sheets	21,906	23	1

Table 5.8: Project 1, Building 1, Visitors Center: Transportation Shift (continued)

Description of Product	Product Cost (f)	Product in Weight	Shift
		g = f ÷ 956	t = g ÷ 75
	$	Tons	
Flattened Expanded Metal	2,364	2.5	(1)
Galv. Perforated Panels	8,006	8.4	(1)
Steel Bar	9,860	10	(1)
Structural Steel-Wide Flange 2	114,232	119	5
Structural Steel	5,000	5.2	(1)
Hollow Metal Door/Frame	28,043	29	1
Metal Studs	241,214	252	10
Metal Lockers	4,547	4.8	(1)

(1): Less than ½ units, but will be rounded to 1

In Table 5.9, the first column lists the name of products; the second and third columns are the distance between the project site to the manufacturing location (m) and harvesting location (h), respectively. The fourth and fifth columns are the calculated transport energy cost (according to Eq. 5.8) for transporting materials from the manufacturing location (M) and the harvesting location (H) to the project site, respectively. The last column indicating the total embodied transport energy cost is the sum (E) of ‘M’ and ‘H’. Overall, in Project 1, Building 1, the total transport energy cost is $96,531.

Table 5.9: Project 1, Building 1, Visitors Center: Embodied Energy

Description of Product	MR Credit 5: Local/Regional Materials				
	Manufacturing Location in Miles from Project (m)	Harvesting Location in Miles from Project (h)	Transport Energy		
			Manufacturing Location to Project $M = m \times i \times t$	Harvesting Location to Project $H = h \times i \times t$	Total Cost for Each Product $E = M + H$
	Miles	Miles	$	$	$
Rebar	10	N/A	244	N/A	244
Structural Steel- Tube	417	1,408	754	2,546	3,300
Structural Steel- Angle	417	1,408	1,696	5,728	7,424
Structural Steel- Wide Flange 1	417	1,408	9,424	31,821	41,245
Structural Steel- Plate	417	1,408	6,408	21,638	28,046
Steel Stud and Track	270	N/A	732	N/A	732

Table 5.9: Project 1, Building 1, Visitors Center: Embodied Energy (continued)

Description of Product	MR Credit 5: Local/Regional Materials				
	Manufacturing Location in Miles from Project (m)	Harvesting Location in Miles from Project(h)	Transport Energy		
			Manufacturing Location to Project $M = m \times i \times t$	Harvesting Location to Project $H = h \times i \times t$	Total Cost for Each Product $E = M + H$
	Miles	Miles	$	$	$
Steel Perforated Panels	2,400	N/A	2,947	N/A	2,170
Misc Metal	17	1,408	23	1,909	1,932
Steel Angles	498	N/A	646	N/A	225
Stainless Steel Sheets	6,520	N/A	1,062	N/A	2,945
Flattened Expanded Metal	1,430	N/A	646	N/A	646
Steel Bar	N/A	N/A	N/A	N/A	N/A

Table 5.9: Project 1, Building 1, Visitors Center: Embodied Energy (continued)

Description of Products	MR Credit 5: Local/Regional Materials				
	Manufacturing Location in Miles from Project (m)	Harvesting Location in Miles from Project (h)	Transport Energy		
			Manufacturing Location to Project $M = m \times i \times t$	Harvesting Location to Project $H = h \times i \times t$	Total Cost for Each Product $E = M + H$
	Miles	Miles	$	$	$
Galv. Perforated Panels	2,350	N/A	1,061	N/A	1,061
Structural Steel-Wide Flange 2	417	1,408	942	3,182	4,124
Structural Steel	417	N/A	188	N/A	188
Hollow Metal Door/ Frame	1,688	N/A	762	N/A	762

Table 5.9: Project 1, Building 1, Visitors Center: Embodied Energy (continued)

Description of Products	MR Credit 5: Local/Regional Materials				
	Manufacturing Location in Miles from Project (m)	Harvesting Location in Miles from Project (h)	Transport Energy		
			Manufacturing Location to Project $M = m \times i \times t$	Harvesting Location to Project $H = h \times i \times t$	Total Cost for Each Product $E = M + H$
	Miles	Miles	$	$	$
Metal Studs	290	N/A	1,311	N/A	1,311
Metal Lockers	380	N/A	172	N/A	172
Overall	N/A	N/A	14,213	66,824	96,531

5.3.1.2. Building 2

By using the same calculation procedures as Project 1, Building 1, the results of the recycled content and the transport energy cost in Project 1, Building 2 are listed in the following tables. Table 5.10 lists the calculation results of the total recycled steel content, which is $2,331,796 and the total recycled content is $1,869,056. Therefore, the percentage of recycled content is 80.16% of the total construction steel products.

Table 5.10: Project 1, Building 2, Desert Learning Center: Recycled Content for Steel

Description of Products	Product Cost	MR Credit 4: Recycled Content			Recycled
		Post Consumer	Post Industrial	Value	
	$	%	%	$	%
Rebar 1	880,313	80%	20%	792,282	90%
Structural Steel-Plate	217,600	50%	50%	163,200	75%
Structural Steel-Angles	76,160	99%	1%	75,779	99.5%
Structural Steel-Wide Flange	467,840	80%	15%	409,360	87.5%
Structural Steel-Tube	326,400	65%	35%	269,280	82.5%
Structural Steel 1	11,602	60%	40%	9,282	80%
Structural Steel 2	49,936	75%	10%	39,949	80%
Steel Stud and Track	18,090	64%	25%	13,839	76.5%

Table 5.10: Project 1, Building 2, Desert Learning Center: Recycled Content for Steel

Description of Product	Product Cost	MR Credit 4: Recycled Content			Recycled
		Post Consumer	Post Industrial	Value	
	$	%	%	$	%
Miscellaneous Metal 2	1,414	25%	0%	354	25%
Rebar	16,665	0%	0%	0	0
Metal Roof at High Roof	57,000	5%	18%	7,980	14%
Hollow Metal Door/Frame	21,936	25%	10%	6,581	30%
Hinges/Carbon Steel	6,950	23%	8.4%	1,863	27.2%
Metal Framing	32,890	20%	40%	13,157	40%
Overall	2,331,796	N/A	N/A	1,869,056	80.16%

Table 5.11 and Table 5.12 show the calculation results of the transport energy for Project 1, Building 2. Overall, the total transport energy cost for Project 1, Building 2 is $31,696.

Table 5.11: Project 1, Building 2, Desert Learning Center: Transportation Shift

Description of Product	Product Cost (f)	Product in Weight g = f ÷ 956	Shift t = g ÷ 25
	$	Tons	
Rebar 1	880,313	921	37
Structural Steel- Plate	217,600	228	9
Structural Steel- Angles	76,160	80	3
Structural Steel- Wide Flange	467,840	489	20
Structural Steel- Tube	326,400	341	14
Structural Steel 1	11,602	12	(1)
Structural Steel 2	49,936	52	2
Steel Stud and Track	18,090	19	1
Miscellaneous Metals 1	147,000	154	6
Miscellaneous Metal 2	1,414	1	(1)
Rebar	16,665	17	1
Metal Roof at High Roof	57,000	60	2
Hollow Metal Door/Frame	21,936	23	1
Hinges/Carbon Steel	6,950	7	(1)
Metal Framing	32,890	34	1

(1): Less than ½ units, but will be rounded to 1

Table 5.12: Project 1, Building 2, Desert Learning Center: Embodied Energy

Description of Product	MR Credit 5: Local/Regional Materials				
	Manufacturing Location in Miles from Project (m)	Harvesting Location in Miles from Project (h)	Transport Energy		
			Manufacturing Location to Project $M = m \times i \times t$	Harvesting Location to Project $H = h \times i \times t$	Total Cost for Each Product $E = M + H$
	Miles	Miles	$	$	$
Rebar 1	10	232	167	3,880	4,047
Structural Steel- Plate	417	501	1,696	2,038	3,734
Structural Steel- Angle	417	501	565	679	1,244
Structural Steel- Wide Flange	417	501	3,770	4,529	8,299
Structural Steel- Tube	417	501	2,639	3,170	5,809

Table 5.12: Project 1, Building 2, Desert Learning Center: Embodied Energy (continued)

Description of Product	MR Credit 5: Local/Regional Materials				
	Manufacturing Location in Miles from Project (m)	Harvesting Location in Miles from Project (h)	Transport Energy		
			Manufacturing Location to Project $M = m \times i \times t$	Harvesting Location to Project $H = h \times i \times t$	Total Cost for Each Product $E = M + H$
	Miles	Miles	$	$	$
Structure Steel 1	417	501	188	226	414
Structure Steel 2	417	501	377	453	830
Steel Stud and Track	270	N/A	122	N/A	122
Miscellaneous Metal 1	17	1,408	46	3,818	3,864
Miscellaneous Metal 2	17	1,408	8	636	644
Metal Roofing at High Roof	1,073	N/A	970	N/A	970

Table 5.12: Project 1, Building 2, Desert Learning Center: Embodied Energy (continued)

Description of Product	MR Credit 5: Local/Regional Materials				
	Manufacturing Location in Miles from project (m)	Harvesting Location in Miles from project (h)	Transport Energy		
			Manufacturing Location to Project $M = m \times i \times t$	Harvesting Location to Project $H = h \times i \times t$	Total Cost for Each Product $E = M + H$
	Miles	Miles	$	$	$
Rebar 2	225	N/A	102	N/A	102
Hollow Metal Door/ Frame	1,688	N/A	763	N/A	763
Hinges/Carbon Steel	1,600	N/A	723	N/A	723
Metal Framing	290	N/A	131	N/A	131
Overall	N/A	N/A	12,267	19,429	31,696

5.3.2. Project 2: Eugene, OR

In Project 2, the overall material cost is $5,292,338, and the total recycled content value is $3,464,796, which is 65.5% of the total cost of steel products used in Project 2.

Table 5.13: Project 2: Recycled Content for Steel

Description of Product	Product Cost	MR Credit 4: Recycled Content			Recycled
		Post Consumer	Post Industrial	Value	
	$	%	%	$	%
Rebar	1,434,569	75	25	1,255,248	87.5%
Structural Steel	1,211,204	80	15	1,059,804	87.5%
Steel Deck	105,519	100	0	105,519	100%
Dietrich Metal Framing	1,582,240	23.5	6.4	422,458	26.7%
Mfg. Metal Panel	737,640	69	0	508,972	69%
Steel Detention and Frames	221,166	51	0	112,795	51%
Overall	5,292,338	N/A	N/A	3,464,796	65.5%

The transport energy for construction steel products in Project 2 is calculated in Table 5.14 and Table 5.15, and the total transport energy cost for Project 2 is $48,030.

Table 5.14: Project 2: Transportation Shift

Description of Product	Product Cost (f)	Product in Weight $g = f \div 956$	Shift $t = g \div 25$
	$	Tons	
Rebar	1,434,569	1,501	60
Structural Steel	1,211,204	1,267	51
Steel Deck	105,519	110	4
Dietrich Metal Framing	1,582,240	1,655	66
Mfg. Metal Panel	737,640	772	31
Steel Detention and Frames	221,166	231	9

Table 5.15: Project 2: Embodied Energy

Description of Product	MR Credit 5: Local/Regional Materials	
	Manufacturing Location in Miles from Project (m)	Transport Energy Manufacturing Location to Project $M = m \times i \times t$
	Miles	$
Rebar	80	2,170
Structural Steel	N/A	N/A
Steel Deck	620	1,121
Dietrich Metal Framing	N/A	N/A
Mfg. Metal Panel	2,380	33,349
Steel Detention and Frames	2,800	11,390
Overall	N/A	48,030

5.3.3. Project 3: Kansas City, MO

Table 5.16 shows the calculation results for the recycled content of construction steel in Project 3. The overall material cost is $45,588, and the total recycled content value is $33,466, which is 73.41% of the total costs of steel products used in Project 3.

Table 5.16: Project 3: Recycled Content for Steel

Description of Product	Product Cost	MR Credit 4: Recycled Content			Recycled
		Post Consumer	Post Industrial	Value	
	$	%	%	$	%
Reinforcing Steel	3,637	91.4%	8.6%	3,481	95.7%
Vulcraft Bar Joist	1,560	99.70%	0%	1,555	99.7%
Vulcraft Metal decking	945	68%	0%	643	68%
Anchor Bolts	4,920	0%	0%	0	0%
Columns and Beams	23,179	99%	0%	22,947	99%
Reinforcing Steel	45	100%	0%	45	100%
Galvmet Galvanized	612	25%	0%	153	25%
Hollow Metal Frames	1,280	25%	10%	384	30%
Metal Stud Framing	9,410	36.90%	16.70%	4,258	45.25%
Overall	45,588	N/A	N/A	33,466	73.41%

5.4. Stage 3: Maintenance and Replacement Process

The material-flow in Stage 3: Maintenance and Replacement Process, is documented in Table 5.17, which is published in "*Life-Cycle Assessment for Steel Construction: Final Report*" (Sansom and Meijer, 2001). The first column in Table 5.17 lists the name of the steel products; the second column shows the life span of the products; the third column lists the steel losses because of corrosion, abrasion, or other kinds of damage; the fourth column lists the fixings of selected products in the maintenance, replacement and repair processes in any given project according to the function necessities. Overall, in the Maintenance and Replacement Process, 0.243% of the steel products will be lost as "leaks", and 0.114 kg of steel will be used to fix 1 kg of the steel product, which makes up the "feeds" in this stage.

Table 5.17: Steel Products' Losses and Replacement in Maintenance Process
(Source: Sansom and Meijer, 2001)

Product	Life span	Losses (%)	Fixings (kg/kg)
Girder	75	0.2	0.118
Lintel	75	0.2	0.118
Road barrier	15	0.5	0.358
Post coated inner wall box	20	0.2	0.118
Door frames	40	0.2	0.118
Insulated inner wall box	20	0.2	0.118
Metal stub wall	75	0.2	0.118
Services	20	0.2	0.118
Light gauge steel (housing)	75	0.2	0.118
Purlins and rails	75	0.2	0.118
Composite floor decking	75	0.4	0.098
Composite sandwich cladding panels	20	0.433	0.097
Roof plate (coated)	20	0.283	0.088
Profiled cladding and roofing panels	20	0.283	0.088
Tapered beam/girder	20	0.283	0.152
Heave structure sections	75	0	0
Average number		0.234	0.114

5.5. Stage 4: Deconstruction Process

Deconstruction is a process of selectively and systematically disassembling buildings to collect materials that are valuable for reusing or recycling in the new construction or rehabilitation of other structures. The rate of waste material flowing to the recycling and reuse facilities is equal to the amount of waste steel sent to the facilities divide total waste steel product, shown as Eq. 5.9. The transport energy is the sum of energy used to transport to recycling facilities and to landfills, and each of them is equal to distance times freight rate, then times shift, shown as Eq. 5.10. The Waste Reduction Progress Report for Project 4 is able to show all the necessary information for calculation.

Rate of waste steel recycled = the amount of recyclable steel
÷ total amount of waste steel (Eq. 5.9)

Transport energy = distance to recycling facilities × freight rate
× shift to facilities + distance to landfills × freight rate
× shift to landfills (Eq. 5.10)

5.5.1. Project 4: Kansas City, MO

The data offered by Project 4 are about the general metal products, which include aluminum, steel, and copper. The construction steel products take the largest portion among all the products, at 90%.

Table 5.18 is the Waste Reduction Progress Report from Project 4. From this table, the total amount of waste steel is 66.6 tons and the total amount of recyclable steel is 63 tons; therefore, according to Eq. 5.9, the amount of steel waste sent to the reuse and recycling facilities is 94.6% of the total steel products,

$$63 \div 66.6 = 94.6\%$$

Table 5.18: Project 4: Waste Reduction Progress Report

Time schedule	Metals	Construction Steel	Recyclable
	Tons	Tons	
8/3/2006	4	3.6	N
10/13/2006	5	4.5	Y
10/20/2006	(1)	(1)	Y
12/14/2006	3	2.7	Y
1/3/2007	4	3.6	Y
3/12/2007	9	8.1	Y
5/10/2007	5	4.5	Y
6/28/2007	7	6.3	Y
6/28/2007	3	2.7	Y
7/16/2007	2	1.8	Y
8/6/2007	5	4.5	Y
8/6/2007	7	6.3	Y
8/9/2007	2	1.8	Y
8/17/2007	3	2.7	Y
9/26/2007	5	4.5	Y
10/3/2007	2	1.8	Y
10/21/2007	3	2.7	Y
11/2/2007	3	2.7	Y

Table 5.18: Project 4: Waste Reduction Progress Report (continued)

Time schedule	Metals	Construction Steel	Recyclable
	Tons	Tons	
11/29/2007	4	3.6	Y
1/8/2008	2	1.8	Y
3/10/2008	2	1.8	Y

(1): Less than ½ units, but will be rounded to 1

According to the report, metals were sent to the reuse and recycling facility for recycling 12 times and disposed in the landfill once. The average distance from the project site to the reuse and recycling facility is 14.9 miles and to the landfill is 30 miles. Therefore, based on Eq. 5.10, the total embodied transport energy cost is,

$$\text{Transport energy} = 14.9 \text{ miles} \times \$0.452/\text{mile} \times 12 + 30 \text{ miles} \times \$0.452/\text{mile} \times 1$$
$$= \$95$$

5.6. Stage 5: Recycling and Reuse Process

The recycling process has already been integrated in the steel manufacturing process because the use of scrap lowers the demand for raw materials and conserves energy. In the steel industry, steel scraps are utilized in one of two types of primary manufacturing processes (Basic Oxygen Furnace and Electric Arc Furnace) to make new steel (Fruehan, 1998). The Electric Arc Furnace is able to utilize virtually 100 percent of the scraps, while the Basic Oxygen Furnace process utilizes approximately 30 percent of the scraps to make new steel (EPA, 2009). The SRI has been tracking and evaluating the steel recycling rate in the U.S. for many years. Table 5.19 shows the recycling rate of two widely used construction steel products. Based on Assumption 3, the data of 2006 will be used. Therefore, the structural steel recycling rate is 97.5% and the reinforcement steel recycling rate is 65%.

Table 5.19: Steel Recycling Rates at a Glance
(Source: Steel Recycling Institute, 2007)

Year	Construction Structural Rates %	Construction Reinforcement Rates %
2003	96	60
2004	97.5	63
2005	97.5	65
2006	97.5	65
2007	97.5	65

This thesis will use Assumption 4 and the same calculation procedures as Stage 1 to calculate the transport energy consumption in Stage 5. Table 5.20 and Table 5.21 show the total quantity/value of scrap imports and exports in 2005 and 2006, respectively (Source: American Iron and Steel Institute, 2006). In both tables, the fourth column shows the data used to calculate transport energy, and ‘a’ and ‘b’ stands for the imports and exports, respectively.

Table 5.20: U.S. Imports of Iron and Steel Scrap, by Country[1], 2006
(Source: American Iron and Steel Institute, 2006)

Country	2005		2006	
	Quantity	Value	Quantity (a)	Value
	Thousand Metric Tons	Thousand USD	Thousand Metric Tons	Thousand USD
Argentina	(2)	201	(2)	155
Bahamas	3	351	5	676
Belgium	36	9,780	61	15,700
Brazil	1	774	(2)	172
Canada	2,750	570,000	3,140	766,000
China	2	978	4	796
Colombia	1	118	2	1,060
Denmark	--	--	137	36,700
Dominican Republic	31	6,900	28	6,310
Ecuador	(2)	102	(2)	76
Egypt	1	732	3	2,280
Estonia	--	--	10	3,040
Finland	1	93	(2)	13

Table 5.20: U.S. Imports of Iron and Steel Scrap, by Country, 2006 (continued)

Country	2005		2006	
	Quantity	Value	Quantity (a)	Value
	Thousand Metric Tons	Thousand USD	Thousand Metric Tons	Thousand USD
France	(2)	358	--	--
Germany	2	148	4	1,050
Italy	(2)	72	(2)	200
Japan	1	1,540	3	1,920
Malaysia	2	264	(2)	93
Mexico	145	61,000	236	95,000
Netherlands	222	72,300	243	62,000
Russia	35	10,500	(2)	67
South Africa	4	35	--	--
Spain	(2) [r]	8 [r]	2	657
Sweden	261	71,500	266	67,700
Taiwan	1	396	1	470
Trinidad and Tobago	1	647	10	2,580
United Arab Emirates	(2)	170	1	728

Table 5.20: U.S. Imports of Iron and Steel Scrap, by Country, 2006 (continued)

Country	2005		2006	
	Quantity	Value	Quantity (a)	Value
	Thousand Metric Tons	Thousand USD	Thousand Metric Tons	Thousand USD
United Kingdom	338	97,200	650	178,000
Venezuela	1	1,560	--	147
Other	2	1,690 r	7	2,130
Total	3,840	909,000	4,820	1,250,000

(r): Revised
(--): Zero
(1): Data are rounded to no more than three significant digits; may not add to totals shown
(2): Less than ½ unit, but will be rounded to 1

Table 5.21: U.S. Exports of Iron and Steel Scrap, by Country[1], 2006
(Source: American Iron and Steel Institute, 2006)

Country	2005		2006	
	Quantity	Value	Quantity (b)	Value
	Thousand Metric Tons	Thousand USD	Thousand Metric Tons	Thousand USD
Bahamas	2	462	10	2,210
Bangladesh	28	7,320	246	19,200
Belgium	13	3,710	4	4,230
Brazil	10	2,410	6	1,270
Canada	2,160	264,000	1,500	285,000
Chile	1	177	(2)	333
China	3,530	1,260,000	3,420	1,600,000
Colombia	51	11,900	67	15,600
Dominican Republic	1	192	5	1,560
Egypt	208	52,500	392	98,600
Finland	65	97,900	50	76,900
France	4	4,610	37	7,560
Germany	7	3,260	3	3,890
Greece	23	4,310	227	51,900

Table 5.21: U.S. Exports of Iron and Steel Scrap, by Country, 2006 (continued)

Country	2005		2006	
	Quantity	Value	Quantity (b)	Value
	Thousand Metric Tons	Thousand USD	Thousand Metric Tons	Thousand USD
Guatemala	(2)	202	(2)	103
Hong Kong	49	31,200	137	64,100
India	806	221,000	618	168,000
Indonesia	188	46,200	115	33,400
Ireland	1	549	1	574
Italy	137	36,900	102	46,000
Japan	41	28,700	51	51,800
Kenya	71	12,800	24	15,000
Korea, Republic of	1,130	316,000	1,350	191,000
Malaysia	457	109,000	907	202,000
Mexico	1,500	287,000	1,110	247,000
Netherlands	21	18,300	12	19,000
Pakistan	39	10,300	70	18,000
Panama	(2)	43	1	220
Peru	44	10,000	64	15,500

Table 5.21: U.S. Exports of Iron and Steel Scrap, by Country, 2006 (continued)

Country	2005		2006	
	Quantity	Value	Quantity (b)	Value
	Thousand Metric Tons	Thousand USD	Thousand Metric Tons	Thousand USD
Portugal	21	4,120	23	4,970
Qatar	31	6,560	--	--
Saudi Arabia	32	7,220	36	6,980
Singapore	75	2,130	54	4,810
Spain	18	15,100	32	26,800
Sweden	7	5,640	(2)	660
Switzerland	(2)	283	1	481
Taiwan	283	153,000	716	244,000
Thailand	337	77,500	461	109,000
Turkey	1,500	299,000	2,470	566,000
Turks and Caicos Islands	2	176	(2)	38
United Arab Emirates	3	688	1	403
United Kingdom	9	6,080	23	6,020
Venezuela	6	1,540	2	551

Table 5.21: U.S. Exports of Iron and Steel Scrap, by Country, 2006 (continued)

Country	2005		2006	
	Quantity	Value	Quantity (b)	Value
	Thousand Metric Tons	Thousand USD	Thousand Metric Tons	Thousand USD
Vietnam	26	7,570	462	13,600
Other	17	5,670	58	8,580
Total	13,000	3,430,000	14,900	4,230,000

(--): Zero
(1): Data are rounded to no more than three significant digits; may not add to totals shown
(2): Less than ½ unit, but will be rounded to 1

Table 5.22 and Table 5.23 show the results of calculations for transport energy cost of importing and exporting scraps in 2006. In those tables, ‘c’ is the construction products rate; ‘j’ and ‘k’ represent the amount of imports and exports of construction steel, respectively; ‘e’ is the estimated distance; ‘i’ is the freight rate; ‘w’ is the cargo ship size; ‘m’ and ‘n’ are the transport energy costs for importing or exporting scraps from other countries, respectively.

Table 5.22: U.S. Imports of Scrap, Embodied Transport Energy Calculation in Construction Industry, by Country[1]

Country	Quantity j = a × c	Average Distance[3] (e)	Embodied Energy m=j×e×i/w
	Thousand Metric Tons	Miles	Thousand USD
Argentina	(2)	5,450	32
Bahamas	1	1,558	9
Belgium	12	4,677	332
Brazil	(2)	4,273	25
Canada	628	1,523	5,655
China	1	7,215	43
Colombia	(2)	2,822	17
Denmark	27	4,681	747
Dominican Republic	6	2,055	73
Ecuador	(2)	3,021	18
Egypt	1	6,799	40
Estonia	2	5,023	59
Finland	(2)	4,751	28

Table 5.22: U.S. Imports of Scrap, Embodied Transport Energy Calculation in Construction Industry, by Country (continued)

Country	Quantity j = a × c	Average Distance[3] (e)	Embodied Energy m=j×e×i/w
	Thousand Metric Tons	Miles	Thousand USD
Italy	(2)	5,343	32
Japan	1	6,247	37
Malaysia	(2)	9,296	55
Mexico	47	1,075	299
Netherlands	49	4,676	1355
Russia	(2)	5,612	33
Spain	1	4,754	28
Sweden	53	4,580	1,435
Taiwan	(2)	7,537	45
Trinidad and Tobago	2	2,915	34
United Arab Emirates	(2)	7,771	46
United Kingdom	130	4,348	3,342
Other	1	N/A	N/A
Total	968		13,848

(1): Data are rounded to no more than three significant digits; may not add to totals shown
(2): Less than ½ unit, but will be rounded to 1
(3): Distance is estimated by http://www.convertunits.com/distance

Table 5.23: U.S. Exports of Scrap, Embodied Transport Energy Calculation in Construction Industry, by Country[1]

Country	Quantity k = b × c	Average Distance[3] (e)	Embodied Energy n=k × e × i/w
	Thousand Metric Tons	Miles	Thousand USD
Bahamas	2	1,558	18
Bangladesh	49	8,142	2,369
Belgium	1	4,677	28
Brazil	1	4,273	25
Canada	300	1,523	2,702
Chile	(2)	4,970	29
China	684	7,215	29,180
Colombia	13	2,822	217
Dominican Republic	1	2,055	12
Egypt	78	6,799	3,136
Finland	10	4,751	281
France	7	4,784	198
Germany	1	4,850	29
Guatemala	(2)	1,603	9
Greece	45	5,873	1,563

Table 5.23: U.S. Exports of Scrap, Embodied Transport Energy Calculation in Construction Industry, by Country (continued)

Country	Quantity k = b × c	Average Distance[3] (e)	Embodied Energy n=k × e × i/w
	Thousand Metric Tons	Miles	Thousand USD
Hong Kong	27	7,821	1,249
India	124	8,422	6,175
Indonesia	23	9,187	1,249
Ireland	(2)	4,156	25
Italy	20	5,343	632
Japan	10	6,247	369
Kenya	5	8,514	252
Korea, Republic of	270	6,386	10,195
Malaysia	181	9,296	9,949
Mexico	222	1,075	1,411
Netherlands	2	4,676	55
Pakistan	14	7,678	636
Panama	(2)	2,260	274
Peru	13	3,570	13
Saudi Arabia	7	7,448	308
Portugal	5	4,591	136

Table 5.23: U.S. Exports of Scrap, Embodied Transport Energy Calculation in Construction Industry, by Country (continued)

Country	Quantity $k = b \times c$	Average Distance[3] (e)	Embodied Energy $n=k \times e \times i/w$
	Thousand Metric Tons	Miles	Thousand USD
Singapore	11	9,417	612
Spain	6	4,754	169
Sweden	(2)	4,580	27
Switzerland	(2)	4,978	29
Taiwan	143	7,537	6,373
Thailand	92	8,623	5,691
Turkey	494	6,321	18,463
Turks and Caicos Islands	(2)	1,876	11
United Arab Emirates	(2)	7,771	46
United Kingdom	5	4,348	129
Venezuela	(2)	2,830	17
Vietnam	92	8,429	4,585
Other	12	N/A	N/A
Total	2,980	N/A	107,874

(--): Zero
(1): Data are rounded to no more than three significant digits; may not add to totals shown
(2): Less than ½ unit, but will be rounded to 1
(3): Distance is estimated by http://www.convertunits.com/distance

5.7. Summary of Calculation

In the case study, this thesis tracked the material-flow and the embodied energy consumption of steel throughout its life span. During the calculation processes, all analysis is given to each individual product. Based on Assumption 2, the average number of the results for different products at the corresponding stage will be used to represent the general situation of that stage, as Eq. 5.11 listed below,

$$\boldsymbol{C} = \frac{\sum_{1}^{n} C_i}{n} \qquad \text{(Eq. 5.11)}$$

Where, 'C' is the average of all relevant factors; 'C_i' is the individual factor; and 'n' is number of total factors. Overall, all the calculation results are summarized below.

5.7.1. Material-Flow for Construction Steel Products

In the Manufacturing process, to make 1 kg of steel products, the Rebar/Wire Rod consumes 1.9 kg of raw materials, the BF Sections consume 1.9 kg, and the EAF Sections consume 4.6 kg. Therefore, according to Eq. 5.9, the average raw materials consumption is,

(1.9 + 1.9 + 4.6) / 3 = 2.8 kg

At the same time, the Rebar/Wire Rod emits 0.4 kg of waste into the environment, the BF Sections emit 0.2 kg, and the EAF Sections emit 0.45 kg. Therefore, the average emission is,

$$(0.4 + 0.2 + 0.45) / 3 = 0.35 \text{ kg}$$

In the Construction Process, Table 5.24 lists the recycled content of each project, and the average recycled content is 0.74 kg/kg. This number indicates the inputs from the recycling and reuse facilities to the construction products.

Table 5.24: Construction Material Input: Steel Scrap Recovered from Reuse and Recycling Facilities

Project	Input Cost	Total Steel Product Cost	Recycled Content
	$	$	kg/kg[1]
Project 1, Building 1	3,495,810	4,296,218	0.81
Project1, Building 2	1,869,056	2,331,796	0.80
Project 2	3,464,796	5,292,338	0.66
Project 3	33,466	45,588	0.73
Overall	8,863,128	11,965,940	0.74

(1) $/$ is equal to kg/kg or 100 %

In the Maintenance process, Table 5.17 shows the amount of steel inputs and outputs. The average steel loss is 2.34×10^{-3} kg/kg, and the repair is 0.114 kg/kg.

In the Deconstruction Process, the deconstruction rate is 0.95 kg/kg and 0.05 kg of steel is lost in 1 kg of steel products in the Deconstruction Process.

At the Recycling and Reuse Process, the average recycling rate of the scrap steel is 81% in 2006, as shown in Table 5.19.

Therefore, the material-flow in the steel life cycle are summarized in Table 5.25.

Table 5.25: Material-Flow for the Steel Resource Loop

Processes	Material input	Material output
Manufacture	2.8 kg/kg	0.35 kg/kg
Construction	0.74 kg/kg	N/A
Maintenance	0.114 kg/kg	2.34×10^{-3} kg/kg
Deconstruction	N/A	0.05 kg/kg
Recycling and Reuse	0.81 kg/kg	N/A

5.7.2. Embodied Energy for Construction Steel Products

Based on Assumption 2, the average cost for import is calculated by Eq. 5.10,

Total Embodied Transport Energy Cost ÷ Total amount of products that result in transportation cost (Eq. 5.10)

In the Manufacturing process, the total primary energy for the BF Rebar/Wire Rod is 13.07 MJ/kg, for the BF Sections is 16.53 MJ/kg, and for the EAF Sections is 13.52 MJ/kg. Therefore, the average primary energy is,

(13.07+16.53+13.52)/3 = 14.37 MJ/kg

In Stage 1, the transport energy cost for imports is $29/kg, and the cost for exports is $10/kg. Overall, the average transport energy cost is $26/kg, shown in Table 5.27.

In the Construction Process, Project 1 and 2 offer the data for transporting products from the manufacturing site or the harvesting site to the construction sites. The cost for Project 1, Building 1, is $\$13 \times 10^{-3}$/kg; for Project 1, Building 2, is $\$6 \times 10^{-3}$/kg; for Project 2, is $\$18 \times 10^{-3}$/kg. Therefore, the cost for transporting products from Stage 1 to Stage 2 is $\$12 \times 10^{-3}$/kg. The detail calculation is shown in Table 5.26.

Table 5.26: Embodied Transport Energy Cost, Construction Process

Project name	From Manufacturing site			From Harvesting site			Average cost
	Amount	Total Cost	Unit Cost	Amount	Total Cost	Unit Cost	
	Tons	$	$/kg	Tons	$	$/kg	$/kg
Project 1, Building 1	4,484	29,707	7×10^{-3}	2,604	66,824	26×10^{-3}	13×10^{-3}
Project 1, Building 2	2,438	12,267	5×10^{-3}	2,278	19,429	8×10^{-3}	6×10^{-3}
Project 2	2,614	48,030	18×10^{-3}	N/A	N/A	N/A	18×10^{-3}
Overall	9,536	90,004	9×10^{-3}	4,882	29,502	17×10^{-3}	12×10^{-3}

In the Deconstruction Process, the total embodied transport energy cost for Project 5 is $95, and the total amount of steel transported to the recycling and reuse facility and the landfill is 66.6 tons; therefore, the average cost is,

$$\$95 \div 66.6 \times 10^{3}\,\text{kg} = \$1 \times 10^{-3}/\text{kg}$$

In the Recycling and Reuse Process, the calculation method for the cost is the same as the Manufacturing process. According to Eq. 5.10, the transport energy cost for imports is $36/kg, and for exports, it is $14/kg. Therefore, the average unit transport energy cost is $30/kg. The results of detail calculations are shown in Table 5.27.

Table 5.27: Embodied Transport Energy Cost, Product Process and Recycling and Reuse Process

Process	Import			Export			Average cost
	Amount	Transport Energy Cost	Unit Cost	Amount	Transport Energy Cost	Unit Cost	
	Thousand Tons	Thousand USD	$/kg	Thousand Tons	Thousand USD	$/kg	$/kg
Products Transportation	7,684	224,696	29	1,643	16,599	10	26
Scrap Transportation	967	13,848	14	2,963	107,874	36	30

As this thesis discussed before, using currency unit during the whole calculation processes will simplify the calculation, but eventually, all the final results have to be converted to the energy unit. 1 gallon of diesel fuel is about 147 MJ, and costs $2.71. Therefore, the relationship of currency and energy unit is: $1 of diesel fuel contains,

$$147\text{MJ} \div \$2.71 = 54.24\text{ MJ}$$

Overall, after conversion, all the embodied energy for each stage in the steel resource loop is summarized in Table 5.28.

Table 5.28: Embodied Energy Cost for Steel Resource Loop

Processes	Amount MJ/kg	Energy Type
Manufacture	14.37	Primary Energy
	1,410	Transport Energy
Construction	0.651	Transport Energy
Maintenance	N/A	Transport Energy
Deconstruction	0.054	Transport Energy
Recycling and Reuse	1,627	Transport Energy

Chapter 6 Conclusions and Recommendations

This purpose of this thesis was to develop a resource loop by using a case study to represent both the cradle-to-grave model and the cradle-to-cradle model. The resource loop will be used to account all the "leaks" and "feeds" in products' life cycle, thereby identify the barriers of implementing cradle-to-cradle model. The case study incorporated materials and energy data from various LEED projects, public resources and literature review. Through the case study of construction steel products, this thesis has tracked the leaks and feeds through steel products' life spans and indicated the methodologies used to develop the resource loop. Several significant findings will be discussed here. In the end, some recommendations will be given for future research.

6.1. Findings and Conclusions

This thesis only completes a resource loop for construction steel, but the resource loop is flexible enough to be widely used and easily interpreted across the diversity of industry. The conclusions are summarized as following:

a. The leaks and feeds throughout the materials life cycle were identified

The resource loop is capable of accounting all the leaks and feeds at each stage. According to Assumption 1, all the calculations are based on 1 kg of steel products. At Stage 1, the data coming from the life cycle inventory of SRI have already considered the amount of materials that could be recycled in the recycling process.

Therefore, those data are the net amount of inputs or outputs during products' life span. To produce 1 kg of steel products, 2.8 kg of raw materials and chemicals are used, 0.35 kg of waste are emitted to our environment, and 14.37 MJ of the primary energy are consumed. In addition, transporting products consumes a lot of energy due to the distance of international trading— it is about 1,410 MJ, ten times of the primary energy.

At Stage 2, steel produced in Stage 1 is transported to Stage 2, thus 0.651 MJ is consumed in this process. On the construction site, a few scraps are generated when assembling steel products. Some of the scraps are sent to the reuse and recycling facilities, but some are discarded.

At Stage 3, steel will lose 2.34×10^{-3} kg/kg of steel during its function life and 0.114 kg/kg of steel will be used for the functional and aesthetic reasons.

At Stage 4, 95% of the steel are sent to the reuse and recycling facilities and 0.05 kg/kg of steel products are discarded. 0.054 MJ is consumed in total when sending steel scraps to the reuse and recycling facilities as well as to the landfills.

At Stage 5, because 0.95 kg of construction steel products are sent to the recycling and reuse facilities from the Deconstruction Process, and scraps collected in each individual stage are sent here too, which is Feed 5, 0.81 kg of steel is recycled in the end. According to Assumption 2, the total recycling rate is the average of Feed 5 and the deconstruction rate, therefore, Feed 5 could be calculated as following,

$$(0.95 \text{ kg} + \text{Feed } 5) \div 2 = 0.81 \text{ kg}$$

$$\text{Feed } 5 = 0.67 \text{ kg/kg}$$

Similar to Stage 1, the transportation consumes a large amount of energy, which is 1,627 MJ/kg.

At the end, the total amount of steel fed back into the beginning point of the resource loop is determined by Project 1, 2, and 3, which is 0.74 kg. Considering that 0.81 kg of steel is recycled, thus, Leak 5 is,

$$\text{Leak } 5 = 0.81 \text{ kg} - 0.74 \text{ kg} = 0.07 \text{ kg}$$

Therefore, the “leaks” and “feeds” are summarized in Table 6.1.

Table 6.1: Summary of Leaks and Feeds in Steel Resource Loop, Based on 1 kg of Construction Steel Products

	Material		Energy	
	Amount	Category	Amount	Category
Leak 1	0.35 kg	Chemicals Raw materials	14.37 MJ	Energy for Manufacturing Process
			1,410 MJ	Transportation
Feed 1	2.8 kg	Chemicals	N/A	N/A
Leak 2	N/A	N/A	0.651 MJ	Transportation
Feed 2	N/A	N/A	N/A	N/A
Leak 3	2.34×10^{-3} kg	Steel Products	N/A	N/A
Feed 3	0.114 kg	Steel products	N/A	N/A
Leak 4	0.05 kg	Steel products	0.054 MJ	Transportation
Feed 4	N/A	N/A	N/A	N/A
Leak 5	0.07 kg	N/A	1,627 MJ	Transportation
Feed 5	0.67 kg	Steel scrap	N/A	N/A

b. A resource loop is developed based on the leaks and feeds identified in the case study

Each product has its own resource loop, but the developing methodologies are similar. In the case of construction steel products, the resource loop is divided into five stages: Construction Steel Product Manufacturing, Construction Process, Maintenance and

Replacement, Deconstruction Process, and Recycling and Reuse Process. The leaks and feeds within the loop are identified in Table 6.1, thus, the proposed resource loop (Fig 4.1) is accomplished in Figure 6.1. In this resource loop, the Manufacturing Process is set as the beginning of the steel products' life spans, and the dashed-line arrow represents the main stream of construction steel flow. The numbers next to the dashed-line without boxes show the amount of steel products in the main stream. At the very beginning point, there is 1 kg of steel products flowing in the loop, then, the main stream accepts new feeds and emits leaks at each different stage. When the main stream passes the Deconstruction Process, there is 0.95 kg flowing in the loop. With the effects from Feed 5, the final amount flowing into the reuse and recycling facilities is 0.81 kg. To the end, the total amount returned back to the Manufacturing Process is 0.74 kg.

There are two other types of arrows indicating the leaks and feeds in the figure: single-line arrows and double-line arrows. The amount of resource flowing in double-line arrows are more than that in the single-line arrows. For example, at Stage 2, Leak 2 includes scrap, other solid wastes and energy consumption, but only a few scraps will be recovered as Feed 5, therefore, the arrow from the Construction Process is a double-line, and the arrow pointing to Feed 5 is a single-line. Feed 5 is the summary of Leak 2, Leak 3, and Leak 4, thus, each arrow pointing to Feed 5 is a single-line and the arrow pointing to the Recycling and Reuse Process is a double-line. The numbers in the boxes show the amount of material-flow and primary energy consumption. They make up “feeds” and “leaks” in the resource loop.

Transport energy is consumed when transporting products within different stages, shown in the dashed-line boxes next to the main stream. It makes up a “leak” of the resource loop, too.

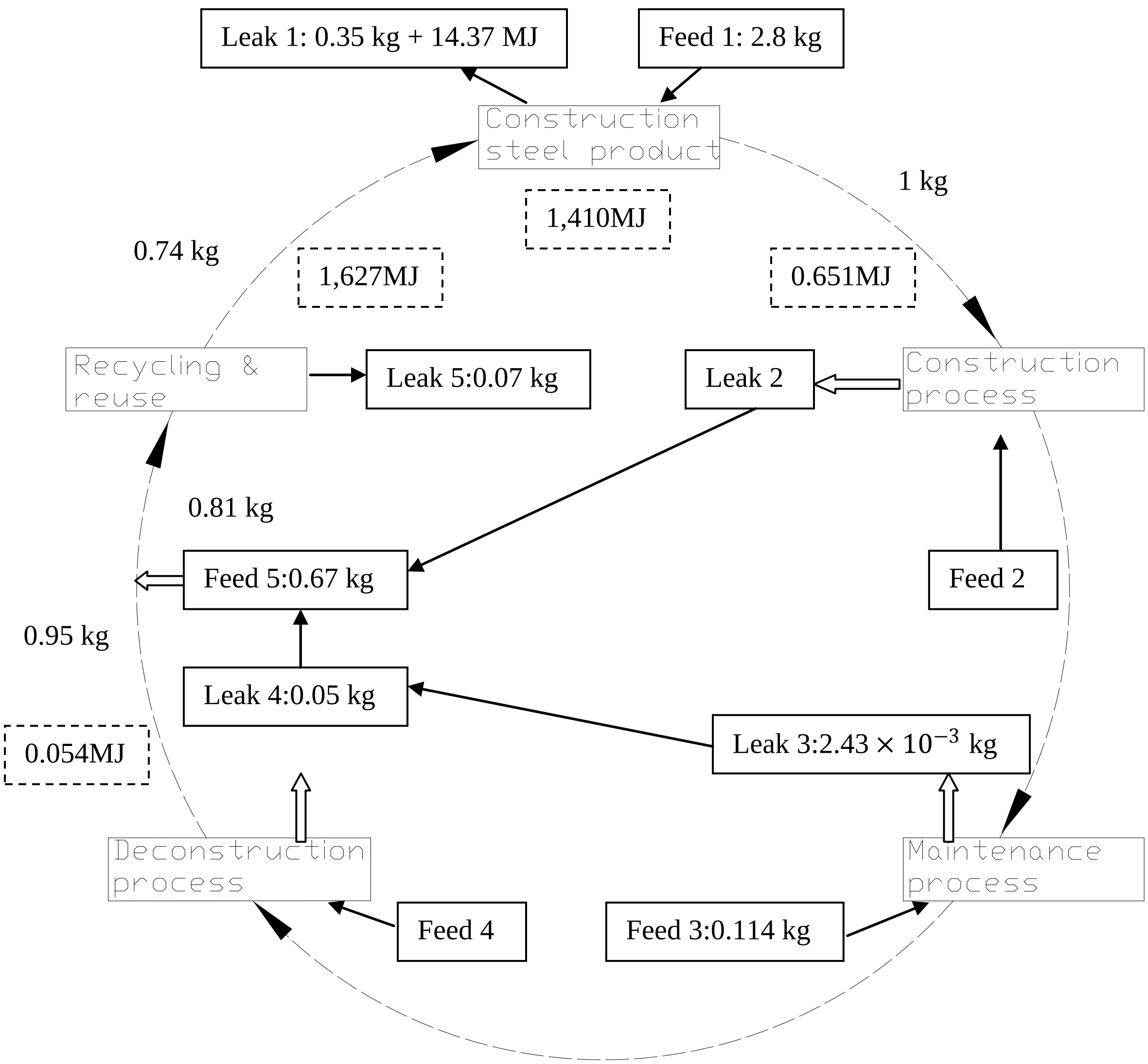

Figure 6.1: Resource Loop for Steel Construction Products

c. From the resource loop of construction steel products (Fig. 6.1), the barriers of implementing cradle-to-cradle model are identified

The first barrier is that the transportation generates significant amount of leaks in the resource loop, and greatly influents the cradle-to-cradle design. Among those energy uses, the international transport energy, which is provided for Manufacture and Recycling and Reuse process, costs more than one thousand times of the domestic transport energy provided for other stages. When choosing products, designers should not only consider their environmental influences; but also the locations of their related manufacturers or recycling facilities. In addition, the previous researches indicate the industry can reduce reliance on raw resources and negative impacts caused by producing new products by intensifying recycling and reuse process. However, compared to the Manufacturing process, this thesis found out the transport energy for Recycling and Reuse process consumes about 200 MJ more. It indicates that many negative impacts can be caused by transporting recycled content to manufacturing process. This result will make designers rethink the importance of recycling products. Whether we should use recycled contents dependent on which one is more: the negative impacts reduced by recycling or the negative impacts increased by the transport energy. In those domestic transports, energy used for transporting to Recycling and Reuse process is less than to Construction process. From this thesis, we can see there are two reasons. First, after Deconstruction process, the amount of steel products is not as many as that at the Construction process, because some of them are lost as “leaks”. Another reason is the transport distance. The steel products used in construction site are shipped from various manufacturers or suppliers because construction requirement for different types of steel products ,but after

Deconstruction process, the receivers for steel waste are mainly recycling and reuse facilities or landfills. Overall, the total transport distance to construction sites is more than to recycling and reuse facilities as well as landfills.

The second barrier is that the material and energy accounting methods are not comprehensive enough. In the process of developing the steel resource loop, this thesis integrated data from published literatures, public institutes, and real world projects. However, with the limitation of accounting methodologies, some data are still not available. Therefore, the "leaks" and "feeds" of the resource loop cannot be completely identified. Details can be found both in Table 6.1 and Figure 6.1. Taking Stage 2 as an example, both information of Leak 2 and Feed 2 are missing. Actually, equipment operated in the projects consumes energy and labors; products, such as adhesive and painting, are used to fix or assemble steel products. There are leaks and feeds in this stage, but they are very difficult to document. Some projects may withhold the documents of total energy or labor costs, but that information is uncategorized and therefore un-reachable.

The current design still cannot put the cradle-to-cradle model into practice. The basic principle in the cradle-to-cradle model is: "waste is equal to food". This theoretically means: with proper design methodologies, there is no "waste" in the product's life span. However, through the case study, this thesis indicates that the leaks are generated in each stage as material-based, or energy-based. Some of the leaks are collected, then sorted and sent to different recycling and reuse facilities (such as Feed 5), and fed back to a new cycle. Other leaks will leave this product's life cycle permanently, which become "waste", such as energy. This thesis assumes that 1kg of steel product flowing at the very beginning of its life span. The amount of material-flow cannot be identified after the Construction process because of incomplete accounting methodology, but the next two stages: Maintenance and Replacement process; Deconstruction process; as well as the waste collected to send to Recycling and Reuse process can be tracked. Overall, in the construction steel resource loop, there is 0.74 kg of steel products returned back after the steel products flow through all stages and incorporate all feeds and leaks. This number is the result without considering energy consumption. Therefore, based on Eq. 3.4, in the resource loop of construction steel,

$$\mathbf{0 < a < 0.74}$$

From the value of 'a', this thesis suggests that the current resource loop for construction steel product is still under cradle-to-grave model, and the distance is still far. However, this resource loop has already accounted the "leaks" and "feeds" with the product's life cycle, and provided a clear picture for designer to better understand the material and energy flows. Therefore, based on this loop, designers can continue to improving this loop and thereby develop optimal design methodologies to help implement cradle-to-cradle model.

6.2. Recommendations for Future Study

This thesis is directed toward offering a more comprehensive understanding of sustainability and reflecting the cradle-to-cradle model. The resource loop is not the cradle-to-cradle model, but it is a prototype providing a common set of principles for implementing the cradle-to-cradle design. With better understanding and acknowledgment of the real material-flow as well as the amount of energy consumptions, more work needs to be done for implementing the cradle-to-cradle model in the industrial system.

a. Comprehensive accounting methods need to be developed to close the resource loop

The current life cycle assessment tools are not complete enough, so the “feeds” and “leaks” in the resource loop cannot be identified completely. This thesis incorporated information from literature review, real projects, published data, recycling organizations, but some leaks and feeds (such as Leak 2 and Feed 2) are still unavailable. For example, the LEED rating systems provide the benchmark for the construction industry to evaluate how effective materials and resources are recycled, reused, and how to reduce the transport energy cost. Therefore, the LEED spreadsheets are able to provide the material-flow and energy consumption in the Construction and Deconstruction Processes. However, other types of embodied energy, such as electricity or fuel cost for operating equipment are not documented in the LEED spreadsheets. Overall, in order to accomplish the resource loop, all the "feeds" and "leaks" are required to be identified. Reliable and comprehensive accounting methods which could track all the leaks and feeds along the products' life cycle are in large demand.

b. The energy consumption should be reduced by improving energy efficiency, shorten transport distance, and using renewable energy

This thesis identified that a significant amount of energy is consumed during a products life cycle as a leak, which cannot be recovered. Therefore, it is necessary to find methodologies to reduce the consumption of energy, such as, using renewable energy, reducing the transport distance and improving the energy efficiency. A few efforts have been made to apply those methodologies. For example, the LEED NC MandR Credit 5 advocates the use of local materials, and thereby reduces the transport distance to minimize transport energy consumption.

c. Develop a dependent resource network

A resource loop is able to show what materials flow into the resource loop, and what materials flow out of the loop. If the resource loops for all products could be developed in the whole industrial system, based on those flows, the connections of different loops could be built up, and thereby develop a holistic network. The leaks in a resource loop could be designed either flowing into its own loop or other loops as nutrients. Materials could consistently flow within the resource loop, and thereby, there is no waste emitted into our environment. Therefore, the further research for the sustainable design would be how to design materials flow within a resource loop, and how to design the waste from a resource loop flow into a new resource loop as nutrient.

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