EFFECTIVE RECYCLE PLANNING FOR CONSTRUCTION AND DEMOLITION WASTES

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ABSTRACT

Construction and Demolition (C&D) wastes are materials produced in the process of construction, renovation, or demolition of structures (buildings and roads). It also includes materials generated as a result of natural disasters (EPA, 2009 A). Preliminary estimates from the U.S. Environmental Protection Agency (EPA) show that the nation generated more than 160 million tons of building related C&D wastes in 2003. Also, Pennsylvania Department of Environmental Protection (PADEP) estimated that in 2005, Pennsylvania disposed over 2.25 million tons of C&D wastes in its municipal and C&D landfills (PADEP, 2009 A).Though previous studies have shown that it is cost-effective and environmentally friendly for contractors or construction managers to recycle C&D wastes rather than disposing them in landfills, these previous studies, however, paid little or no attention to detailed cost of recycling C&D wastes in a particular geographical area or region as compared to the availability of market for recycled materials or monetary value of the recycled materials.

Hence, the objective of this study was to develop a mathematical model that helps stakeholders in construction business to evaluate the potential cost of recycling C&D waste components in their geographical area or region, and the potential revenue from the recycled materials. The model developed in this thesis will enable private companies or individuals to identify, invest and participate in the recycling of C&D waste components that yield good profits in their region or area. It will also enable Government to identify, sponsor or provide incentives for the recycling of C&D waste components that yield no or less profit in order to reduce environmental pollution and generate jobs.

A case study is conducted in Pennsylvania to test the model developed in this thesis and the test has been successful. Based on the mathematical model and logic structure for selecting C&D waste components for recycling, drywall, roofing shingles and wood are identified as the components whose recycling will yield good profit and thus may not need government’s support or incentives. Moreover, C&D waste components such as concrete, brick, block and asphalt, have been identified as components whose recycling will not be profitable enough and therefore would require government’s support or incentives. The result of the case study also shows that the quantity of non-ferrous metals in C&D wastes are very small and their recycling will not yield any significant profit.

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CHAPTER 1

INTRODUCTION

1.1 Construction and Demolition Waste

The definition for characterization of a waste stream as a Construction and Demolition (C&D) waste or debris may vary from country to country. United State Environmental Protection Agency (EPA) defines C&D wastes as materials produced in the process of construction, renovation, or demolition of structures (buildings and roads). It also includes materials generated as a result of natural disasters (EPA, 2009 A). The components of C&D debris include concrete, masonry, asphalt, wood, brick, metals, wallboard or drywall, glass and plastics.

Preliminary estimates from the U.S. Environmental Protection Agency (EPA) show that the nation generated more than 160 million tons of building related construction and demolition (C&D) materials in 2003. According to the most recent data available (2003), nearly 53 percent of all building-related C&D materials are the result of demolition activities, 38 percent of the materials are produced by renovation activities, while approximately 9 percent are the result of new construction (EPA, 2009 B). Also, Pennsylvania Department of Environmental Protection (PADEP) estimated that Construction and Demolition waste makes up approximately seventeen and a half percent (17.5%) of Pennsylvania municipal waste stream. It stated that in 2005, Pennsylvania disposed of over 2.25 million tons of C&D waste in Pennsylvania municipal and C&D landfills (PADEP, 2009 A).

1.2 Construction and Demolition Waste Management

Due to continuous increase in the volume of C&D waste generated, a well thought out strategy or plan for managing C&D waste is as important as it is to any other aspect of planning and building or construction. Thus, development of a waste management strategy or plan is vital in establishing commitment to waste reduction, recovery, reuse and recycling, not only for economic benefits, but also for resource conservation, environmental and even social benefits. In preparing an effective plan, it is necessary to include waste diversion goals and objectives, exploration of reduction, recycling and reuse alternatives, and identification of locally available recycling and reuse outlets (EPA, 2009 B). Landfill disposal should be considered the last option for disposing C&D waste. Other factors that affect C&D waste management, such as quantity of C&D waste, material type and composition, tipping or disposal fees, labor cost, transportation cost, equipment cost, recycling cost, market for recycled materials, state regulations and environmental impacts or benefits are considered when developing waste management plan.

1.3 Effective Recycle Planning

Effective recycling of C&D waste requires identification of recycling goals and objectives. The goal of recycling planning is to design optimal recycling techniques for processing C&D waste components into recycled materials with marketable or valuable end-use options at cost-effective rate; and thereby reducing the cost of C&D waste disposal, conserving resources, and protecting the environment by diverting C&D waste from landfills. To achieve this goal, it is necessary to determine the percentage of potential or estimated C&D wastes or C&D waste components to be recycled.

1.4 Mathematical Model

A mathematical model is a representation of a system or event in mathematical language. Mathematical models are used in many disciplines, including the natural sciences, social sciences and engineering disciplines. According to Eykhoff (1974), a mathematical model is 'a representation of the essential aspects of an existing system or a system to be constructed which presents knowledge of that system in usable form'. Mathematical models can take many forms, such as dynamical systems, statistical models, differential equations, or game theoretic models. These models and other types of models can overlap; resulting in models with variety of abstract structures (Wikipedia, 2009).

1.5 Problem Statement

United States generated more than 160 million tons of building related construction and demolition (C&D) materials in 2003 (EPA, 2009 B). Most of these C&D waste are disposed at landfills. For instance, Pennsylvania Department of Environmental Protection (PADEP) estimated that Construction and Demolition waste makes up approximately seventeen and a half percent (17.5%) of Pennsylvania municipal waste stream. It stated that in 2005, Pennsylvania disposed over 2.25 million tons of C&D waste in Pennsylvania municipal and C&D landfills (PADEP, 2009 A). This current practice of burying most C&D waste in landfills is not cost-effective to construction managers, contractors or developers as limited capacity of landfills or limited space for new landfills leads to high cost of landfill tipping fees. Also, the current practice is not environmentally or even socially beneficial. With increasing knowledge of the environmental impacts of landfills, many communities are strongly opposing any decision to site any landfill in their communities. This opposition sometimes leads to social unrest between the proponents and opponents of the decision to site landfills in the communities. Hence, stakeholders in construction business are compelled to search for alternative and cost-effective methods of disposing C&D waste in their geographical area or region.

To find solution to the afore-stated problem, there have been several studies or researches conducted on construction and demolition waste management. Many of these studies or researches have identified the environmental impacts of C&D disposal in landfills, and the economic and environmental benefits of recovering, reusing and recycling C&D waste. Most of these studies evaluated the progress and achievements of C&D waste management in terms of tons or percentage diverted to recycling facilities or landfills, tons or percentage reuse or sold directly and the proceeds, and concluded that it is cost-effective to reuse or recycle C&D waste than disposing into landfills. Since it is the responsibility of those who are involved in C&D waste generation to ensure that the waste is effectively disposed, these previous studies therefore recognized an urgent need for all the stakeholders in construction business to participate, invest and promote C&D waste recycling in their geographical area or region.

However, these previous studies paid little or no attention to detailed cost of recycling C&D waste in a particular geographical area or region as compared to the monetary value (dollar value) of selling the recycled materials to available end users. Thus, many of the models are only developed to quantify the potential waste to be generated and comparing the alternative cost of disposal at landfills or recycling facilities; without models for evaluating the potential cost of recycling the C&D waste components in a geographical area or region into marketable end-use options and the potential proceeds from selling the end-use options.

1.6 Scope of Research

The objective of this study is to develop a mathematical model that can help stakeholders in construction business, including developers, contractors, construction managers and government, to evaluate the potential cost of recycling C&D waste components in their geographical area or region, and the potential proceeds from the recycled materials. This research would provide the stakeholders in construction business with a tool for effective planning for the recycling of the C&D waste components in their geographical area or region, by helping them to identify C&D components whose recycling would yield good profits and those that would yield less or no profit in the geographical region or area.

Furnished with the findings of this research, private companies or individuals can invest and participate in the recycling of C&D waste components that would yield good profits in their regions or areas. The Government can then sponsor or provide incentives for the recycling of C&D waste components that yield little or no profit, in order to reduce environmental pollution, conserve natural resources and generate jobs in their geographical areas or regions. As such, the stakeholders in construction industry would be encouraged to promote, participate and invest in recycling of C&D properly, leading to reduction in construction or demolition cost, conservation of resources, creation of employment, and other economic and environmental benefits.

The mathematical model considered factors such as the tipping fees charged at recycling facilities, cost of recycling the recyclable components to recycled materials with market value, and the price or market value of the recycled materials. It also considered the percentage of the total quantity of particular C&D waste components that is recycled to particular recycled materials or end-use options. This study only considered effective planning for offsite recycling of C&D wastes in a particular geographical area or region through the participation of all the stakeholders in construction business. It is hoped that the involvement of all stakeholders would promote proper flow of recyclable and recycled C&D materials in a geographical area or region. It would also enable the Government to regulate disposal of C&D wastes and control the cost of disposing recyclable C&D wastes. Moreover, it would enable the Government to control or regulate the price of recycled materials by providing subsidy or incentives for the recycling of C&D wastes, promoting the use of recycled C&D

materials and supporting research for the development of market for recycled materials that have less or no market in the geographical area or region.

The database generated and used in this research is based on data collected from Pennsylvania Department of Environmental Protection (PADEP), some existing recycling companies in Pennsylvania, publications by Lancaster County Solid Waste Management Authority (LCSWMA), United States Environmental Protection Agency (EPA) and New Jersey Department of Solid & Hazardous Waste.

1.7 Thesis Proposal Layout

Chapter 1 of this thesis introduces the subject matter and gives a clear insight to the research area. The problem statement is presented and the scope of the research is discussed.

Chapter 2 gives detailed information about the background of the research area and relevant previous works. The sections in this chapter include generation of C&D waste, components and composition of C&D waste, C&D waste management, factors that determine the cost of C&D waste disposal, C&D waste recycling, previous related works, observations and remarks.

Chapter 3 deals with methodology. It includes data collection, methods used in collecting the data and the sources of the data, and the mathematical model is developed.

A case study is presented in Chapter 4 to test the mathematical model and the logic structure for selecting C&D waste components for recycling developed in this thesis. The results of the case study are analyzed, discussed and the summary of the results is presented in this chapter.

Chapter 5 is the final chapter of this thesis. It provides concluding remarks and recommendations for further research related to this research.

CHAPTER 2

BACKGROUND/LITERATURE REVIEW

2.1 Generation of Construction and Demolition Wastes

Characterization of a waste stream as a Construction and Demolition (C&D) waste or debris may change from country to country. According to US Environmental Protection Agency (EPA), C&D wastes are materials generated in the process of construction, renovation, or demolition of structures (buildings and roads). These materials are also produced during natural disasters (EPA, 2009 A). Depending on their origin, the sources of C&D waste are categorized as follows:

(i) Demolished Waste: arising from the total or partial demolition of buildings or civil infrastructure. These materials may be pieces of concrete, soil, gravel, metals, water installations material, electrical installations materials, ceramics, coats, bricks, overlay plates, tiles, plasters, sand, stones, etc.

(ii) Wreckage Waste: arising from construction or renovation of buildings or civil infrastructure, including the earth from excavation works. Some of these wastes might be due to errors incurred during the design phase, procurement phase, handling or storage of materials or during the construction operation phase. The materials include concrete, wood, plastics, wallboard or dry wall, ceramics, bricks, tiles, plasters, etc.

(iii) Packaging Waste: arising from packaging or wrapping of materials for delivery. It includes containers, pallets, cans, material wrapping, etc.

Some increases in construction waste are due to decreasing material cost because of efficient production technology as compared to increasing labor cost. As such, designers and construction managers tend to focus much on controlling labor efficiency instead of reducing waste of construction materials. The consequence is that they end up incurring extra cost of disposing the construction waste.

2.2 Components and Composition of C&D Waste

C&D waste components vary depending on the type of building or civil infrastructure constructed or demolished, and the method used for the construction or demolition. Table 2.1 shows typical components of building-related C&D debris (EPA, 1999).

Table 2.1: Typical Components of Building-Related C&D Debris

Materials	**Content Examples**
Wood	forming and framing lumber, stumps, plywood, laminates, scraps
Drywall	sheetrock, gypsum, plaster
Metals	pipes, rebar, flashing, steel, aluminum, copper, brass, stainless steel
Plastics	vinyl siding, doors, windows, floor tiles, pipes
Roofing	asphalt and wood shingles, slate, tile, roofing felt
Rubble	asphalt, concrete, cinder blocks, rock, earth
Brick	bricks, decorative blocks
Glass	windows, mirrors, lights
Miscellaneous	carpeting, fixtures, insulation, ceramic tile

Source: U.S. EPA Characterization of Building and Demolition Debris in the United States, 1999, http://www.epa.gov/epaoswer/osw/pub-c.htm>.

The quantity and qualitative characteristics of C&D waste are influenced by a significant number of parameters, as listed below (Kourmpanis et al., 2008):

(i) Period of construction.

(ii) Main material used for the construction of a building.

(iii) Techniques that are applied for the construction of a building.

(iv) Historical, cultural, economic value and importance of a building.

(v) Location of a building.

A research done by Staley and Barlaz (2009) of North Carolina State University summarized C&D discarded masses and contribution to total waste stream in selected US states including Pennsylvania in Table 2.2. The research also shows the discarded C&D waste stream composition in those states in Table 2.3.

Also, the study done by Camp, Dresser and McKee Inc. on quantity and composition of construction and demolition debris in Wisconsin for the Wisconsin Recycling Market Development Board, 1998, shows the largest materials in the commercial construction waste stream and commercial demolition waste stream in figure 2.1. The same study shows the largest materials in the residential construction waste stream and residential demolition waste stream in figure 2.2.

In addition, the research done by Cascadia Consulting Group for California Environmental Protection Agency on Detailed Characterization of Construction and Demolition Waste, 2006, shows the overview of California's C&D waste stream by subsector, 2005, in figure 2.3. The same research shows overview of waste divertibility;

overall C&D in four major metropolitan areas of California, including the San Diego area, Southern California/Los Angeles Basin, the San Francisco Bay area, and the Central Valley, in figure 2.4.

Table 2.2: C&D Discarded Masses, Per Capita Rates and Contribution to Total Waste Stream.

STATE	STUDY YEAR[a]	C&D MASS DISCARDED[b] (thousand Mg)	C&D Rate (kg $person^{-1}d^{-1}$)	C&D IN TOTAL SOLID WASTE STREAM[c] (%)
California	2003	7,922	0.61	22.1
Delaware	2006	241	0.77	23.5
Florida	2000	3,856	0.66	28.5
Georgia	2005	276	0.08	4.6
Iowa	2005	629	0.58	28.1
Kansas	2001	1,016	1.03	23.8
Minnesota	2000	48[d]	0.03[d]	2.8
Missouri	1998	1,022	0.51	29.0
Oregon	2002	429	0.33	18.9
Pennsylvania	2001	985	0.22	11.6
Wisconsin	2001	1,237	0.63	28.9

a Year in which data were collected which may be different from the publication year.
b Masses are wet basis.
c The percent of discarded MSW + C&D that is C&D.
d These data are likely lower than actual values as C&D waste was not uniformly included in the state studies.
Source: (Staley and Barlaz, 2009)

Table 2.3: Discarded C&D Waste Stream Composition (% By Wet Mass)[a]

Waste Category	Mean State Studies[b]	CA	DE	FL	GA	IA	KS	MN	MO	OR	PA	WS
Concrete/rock/brick	11.3	11.1	9.7	N/A	9.5	N/A	N/A	N/A	15.8	13.7	N/A	12.2
Asphalt products	14.0	8.9	12.3	N/A	N/A	N/A	N/A	N/A	12.2	20.3	N/A	20.9
Lumber	39.7	44.5	52.5	N/A	55.4	25.5	N/A	N/A	27.1	26.5	49.8	47.8
Gypsum board	9.7	7.8	6.6	N/A	8.1	N/A	N/A	N/A	8.7	24.8	9.1	5.9
Soil/Fines	11.5	11.2	4.5	N/A	N/A	N/A	N/A	N/A	27.8	5.6	N/A	N/A
Other C&D	13.8	16.6	14.3	N/A	26.9	74.5[c]	N/A	N/A	8.3	9.2	41.1	13.3
Total	100	100	100	N/A	100	100	N/A	N/A	100	100	100	100

a Data organized by major component category based on the state studies. Totals by component may differ due to rounding or averaging.

b States not reporting data in at least 4 out of 6 categories were excluded in this average (i.e. FL, IA, KS, MN, PA).

c Includes carpet in this category rather than under Durables-Misc./Bulky Items sub-category for MSW.

N/A = Not Available.

Source: (Staley and Barlaz, 2009).

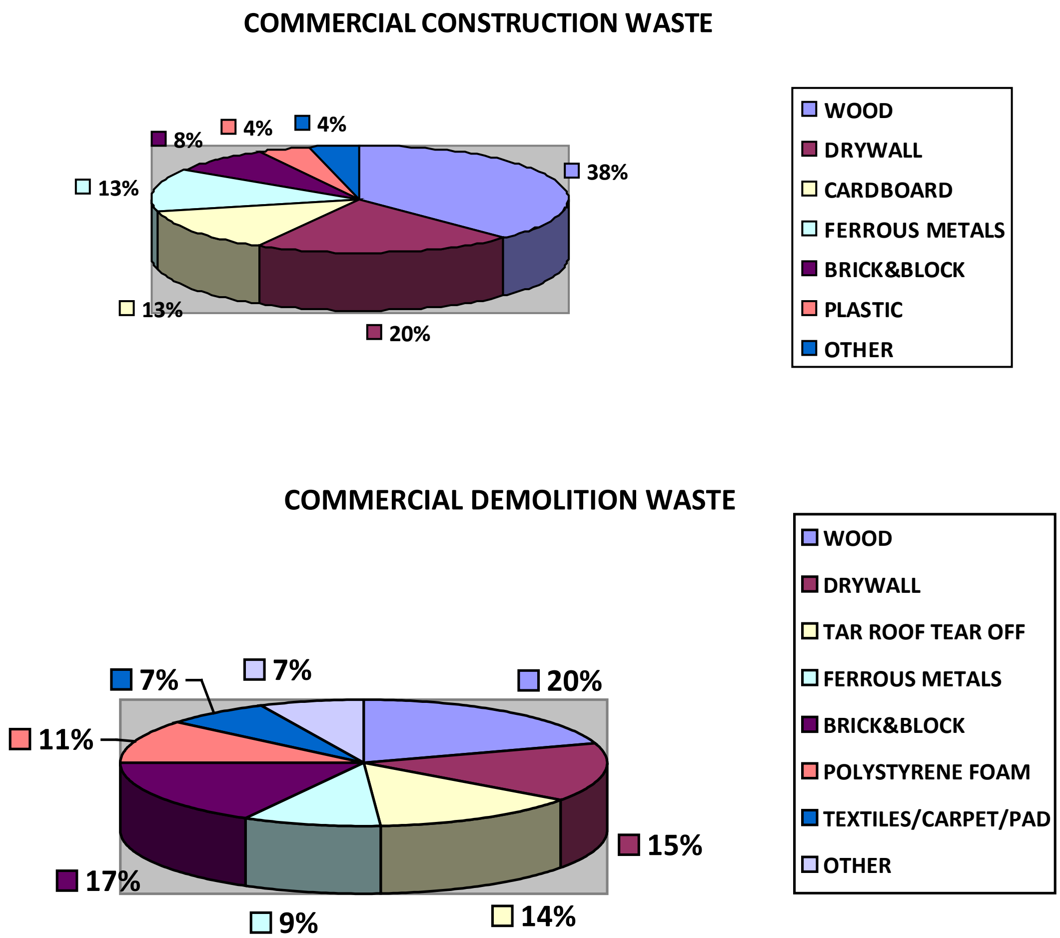
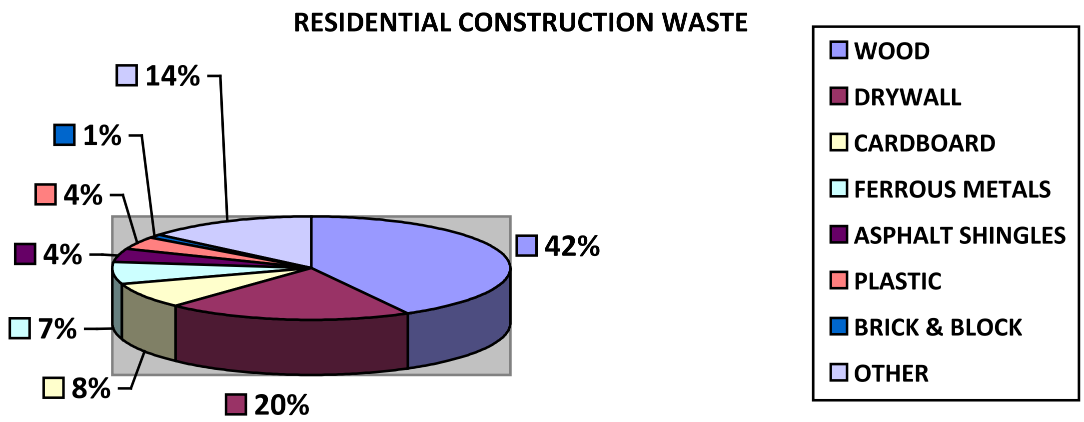


Figure 2.1: The Largest Materials in the Commercial Construction Waste Stream and Commercial Demolition Waste Stream in Wisconsin.

Source: (Camp, Dresser and McKee Inc., 1998).



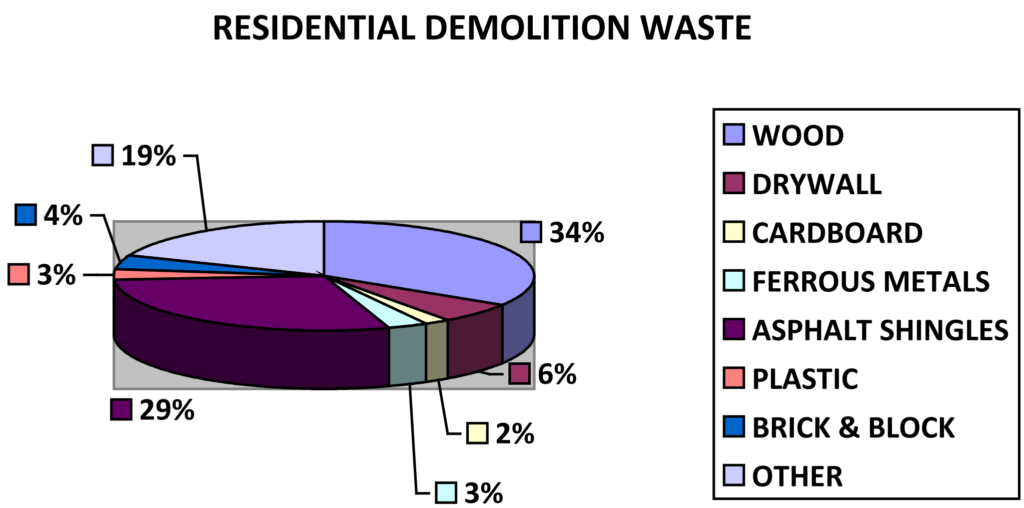


Figure 2.2: The Largest Materials in the Residential Construction Waste Stream and residential Demolition Waste Stream in Wisconsin.

Source: (Camp, Dresser and McKee Inc., 1998).

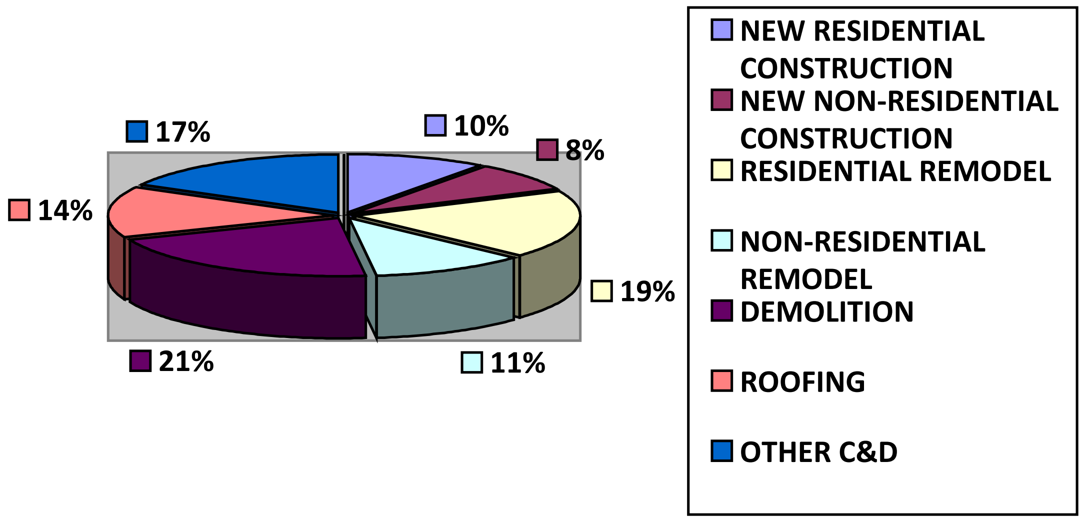


Figure 2.3: The Overview of California's C&D Waste Stream by Subsector, 2005.

Source: (Cascadia Consulting Group, 2006).

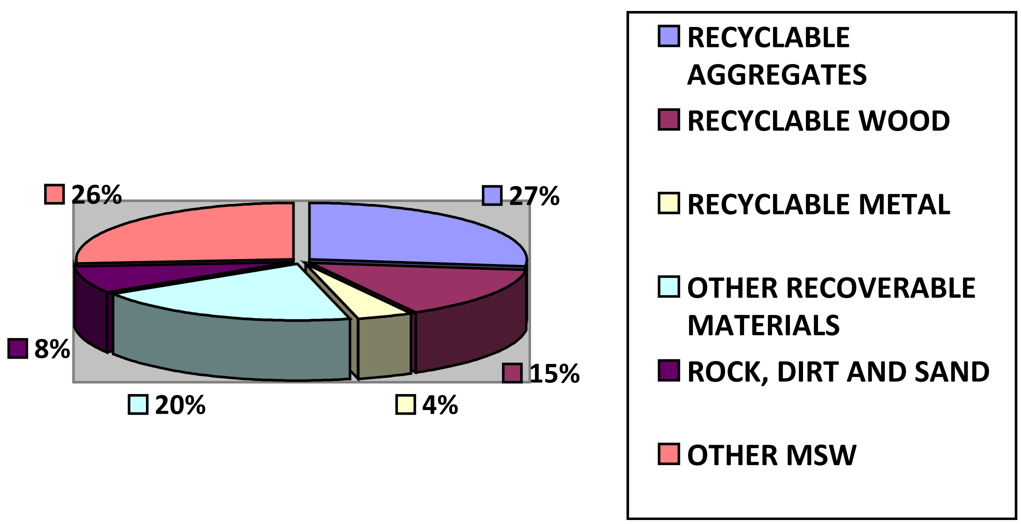


Figure 2.4: The Overview of Waste Divertibility: Overall C&D in Four Major Metropolitan Areas of California.

Source: (Cascadia Consulting Group, 2006).

2.3 Construction and Demolition Waste Management

Due to continuous increase in volume of C&D waste, a well thought out strategy or plan for managing C&D waste is as important as it is to any other aspect of planning and building or construction. Thus, development of a waste management strategy or plan is vital in establishing commitment to waste reduction, recovery, reuse and recycling, not only for economic benefits, but also for environmental, resource conservation and even social benefits.

The main purpose of a C&D waste management plan is to:

(a) Predict the quantities and types of C&D that will be generated during a construction, renovation, or demolition project.
(b) Identify the various available disposal alternatives.
(c) Estimate C&D waste management cost for various available disposal alternatives.
(d) Compare the cost of various available disposal alternatives.
(e) Evaluate the economic and environmental benefits of various available disposal alternatives.
(f) Adopt the best or optimal C&D waste management plan or strategy with the best economic and environmental benefits.

In preparing an effective plan, it is necessary to consider including waste diversion goals and objectives, exploration of recycling and reuse alternatives and identification of locally available recycling and reuse outlets (EPA, 2009B). According to U.S EPA, The following steps are taken to achieve the C&D waste management goals and objectives:

(1) The first step in creating plans is to identify a waste diversion goal for your project. For instance, the goal may be to reuse or recycle fifty percent (50%) of all project C&D waste. Keep the goal realistic, but do not underestimate potential resources. Locally available C&D recyclers are making it possible for area contractors to obtain diversion rates above eighty percent (80%).

(2) A critical second step in developing a C&D waste management plan is to predict the project's waste generation. Break the project down into phases and make the best prediction of types and quantities of wastes that will be generated. Remember that these are estimates and can be revised as necessary.

(3) The next step will be to devise handling procedures for all project wastes. Make sure that there are proper containers and adequate space to implement the C&D waste management plan. Some haulers and recyclers may have special requirements or restrictions on the condition and types of materials they will accept.

(4) The final and the most crucial step will be the identification of a destination for each material that is generated on your project; with focus on, reuse waste components, recycle waste components, recover energy in waste, before considering disposal to landfills as the last options. This sequence for effective C&D waste management alternatives is as shown in figure 2.5.

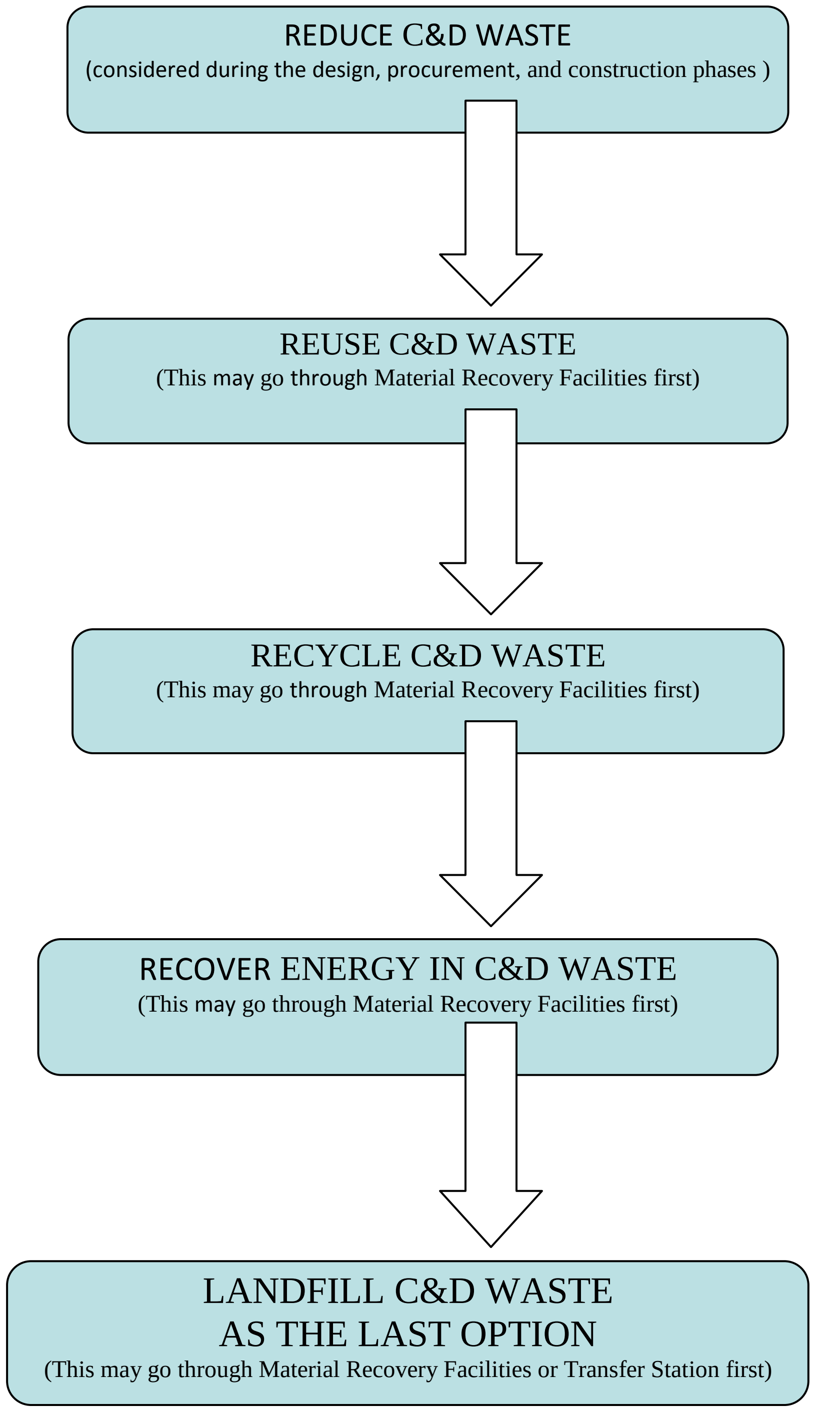


Figure 2.5: Effective Sequence for C&D Waste Management Alternatives.

The effective sequence for C&D Waste management shown in figure 2.5 is designed to achieve maximum resources. The Reduce option aims at minimizing C&D waste generated in the first place. The Reuse option ensures that some useful components of the C&D waste are recovered and used again. These two options come before the materials could be exactly defined as C&D waste. The next option is recycling; which involves the processing of the recyclable materials to valuable materials again. The waste may be disposed in a Material Recovery Facilities first, where different components can be further separated before disposing the required components to the Recycling Facilities. The Energy recovery option requires the burning or processing of the waste to recover or capture the energy for economic usage. The waste may be disposed in a Material Recovery Facilities first, where different components can be further separated before disposing the required components to the Energy Recovery facilities. Generally, C&D wastes are not accepted in Energy Recovery Facilities because of the following reasons (Arsankan, 2003):

(1) Size factor; the hopers in the facilities are not suitable to insert and burn big units, like big pieces of wood or metals.
(2) Most of the C&D wastes do not decompose when burned.
(3) Materials like sheetrock, plywood gypsum cause upsets in the system, causing more hazardous outputs than the system allows.

The remaining option, besides Energy Recovery Facilities, is the Landfill option. The C&D waste may be taken to Material Recovery Facilities first, where different components can be further separated before disposing the required components to different types of Landfills. The wastes may also be taken to Transfer Stations where the wastes are further transferred to various Landfills without separation into different components. Landfills may be designated as hazardous Landfills for hazardous wastes, C&D Landfills for C&D wastes, and Non-hazardous or Municipal Solid wastes Landfills for non-hazardous wastes.

This study will concentrate on the Recycling option. The total estimated cost of recycling the recyclable C&D wastes would be compared to the estimated proceeds or income accruable from selling the recycled materials. Hence, the profit generated from recycling would be determined.

2.4 Factors That Determine the Cost of C&D Waste Disposal

Below are some of the factors that may affect the cost of C&D waste disposals:

State Regulations: There are various regulations that govern the disposal of waste in United States. The regulations may be Federal, State, county or city regulations. Subtitle D of the Resource Conservation and Recovery Act (RCRA) is a federal legislation that regulates proper disposal of solid wastes, including C&D wastes, in United States. The Subtitle D almost exclusively refers to nonhazardous solid waste. Subtitle D covers all wastes not regulated by subtitle C, which regulates hazardous waste and Subtitle I, which regulates petroleum products and other hazardous substances as defined in CERCLA Section 101.

As such, RCRA, Subtitle D covers most Construction and Demolition wastes. Normally, RCRA permits state and local governments to enact their own waste management regulations or by-law respectively, which the states and local governments would be responsible for enforcement (US Army Corps of Engineers, Technical Report, 1999). Thus, every state has different regulations for their waste management policy; since regulations for C&D disposal are instituted at the state level. This research is based on the C&D waste management policy of the Commonwealth of Pennsylvania. More explanations would be given in subsequent Chapters.

Disposal or Tipping Fee: Tipping fee is the money charged by landfill operators for the disposal of C&D waste. The fee is usually charged in dollars per ton ($/ton) and it depends on the location of the landfill. Also, Material Recovery Facilities, Energy Recovery Facilities and Transfer Stations do charge tipping fee. In addition, Recycling facilities may charge or may not charge disposal fee depending on the components of C&D waste. As such, the C&D wastes need to be separated into different components in order to be accepted by recycling facilities. For instance, recycling facilities normally pay the contractors for C&D materials such as steel, while on the other hand the contractors are charged disposal fee for components such as concrete or bricks. Whereby the recycling facilities charged the contractors for disposal of C&D waste components, the tipping fee depends on the component of C&D waste that is disposed.

Transportation Costs: The transportation cost depends on factors such as the hourly rate charged by drivers, the cost of renting or owning a truck, hourly cost of operating and maintaining a truck, the cost of fuel, the distance between the waste generation site and the disposal facility, and other miscellaneous costs such as the distance between the waste generation site and truck park or station. The total transportation cost is gotten by multiplying the hourly costs with the total number of hours required to drive to the landfill or disposal facility; which depends on the distance and the traffic condition of the road. In addition, the time required to load and unload the C&D waste is considered in calculating the total number of hours required to transport the C&D waste.

Labor and Equipment Cost: Labor cost includes the cost of labor required to collect, separate and load the C&D waste or different C&D waste components to landfills or recycling facilities respectively. Moreover, the labor cost for extra work required to prepare specific components of C&D for acceptance by recycling center is also considered in arriving at the total labor cost. Equipment cost is the cost required to rent or own, operate and maintain the equipment use in collecting, separating, loading and unloading the C&D waste; which usually depends on whether the C&D wastes are to be disposed to a recycling facility or a landfill. These costs depend on the hourly rate of each worker, equipment and the time required in performing the tasks.

2.5 Construction and Demolition Waste Recycling

Recycling involves the processing of C&D wastes components into reusable or valuable materials. Recycling can be done onsite or offsite depending on how cost-effective it is to those involved in the construction project; such as the contractor, construction manager, estate developer or the relevant government agencies that are involved in construction, renovation or demolition of buildings and other civil infrastructures.

However, it is not all C&D components or materials that are environmentally suitable for recycling; due to their toxic or hazardous nature. As such, components or materials from C&D wastes are classified as hazardous waste, and requires special handling. Example of such hazardous materials from C&D wastes includes latex paint, chemical solvents, cements, asbestos products and adhesives. Thus, the hazardous materials can be separated and appropriately disposed at hazardous waste processing facilities or hazardous waste landfills, while the remaining recyclable materials or components are recycled either offsite or onsite.

2.5.1 Recyclable C&D Materials and Their End-Use Options

Typical materials recycled from building sites include metal, lumber, asphalt, pavement (from parking lots), concrete, roofing materials, corrugated cardboard and wallboard (EPA, 2009 B). In its publication titled "Recover Your Resources; Reduce, Reuse, and Recycle Construction and Demolition Materials at Land Revitalization Projects," United States Environmental Protection Agency (EPA) identified the following commonly recovered C&D materials and their end-use options or market:

Asphalt Paving**:** Asphalt can be crushed and recycled back into new asphalt. Markets for recycled asphalt paving include aggregate for new asphalt hot mixes and sub-base for paved road. Figure 2.6 shows asphalt paving recycling site. For more information on recycling asphalt, visit www.arra.org (EPA, 2009 B).

Figure 2.6: Asphalt Paving Recycling Site.
Source: (EPA, 2009B).

Wood: Clean, untreated wood can be recycled, re-milled into flooring, or chipped/ground to make engineered board, boiler fuel, and mulch. Timbers, large dimension lumber, plywood, flooring, molding and lumber longer than six feet (6ft) can be reused (EPA, 2009 B). Figure 2.7 shows different sizes of wood arranged at building deconstruction site.

Figure 2.7: Different Sizes of wood Arranged at building Deconstruction Site.
Source: (EPA, 2009B).

Gypsum Wallboard**:** Pieces of gypsum drywalls that remain as waste after construction or removed during demolition can be recycled. Markets include new drywall manufacture, cement manufacture, and agriculture. Unused drywall can be returned to a supplier, donated, or sold. Figure 2.8 shows gypsum wallboard arranged in a container for recycling. For more information on recycling drywall visit www.drywallrecycling.org (EPA, 2009 B).

Figure 2.8: Gypsum Wallboard Arranged in a Container for Recycling.
Source: (EPA, 2009B).

Metals**:** Metals found at a construction, demolition, or renovation sites can be recycled. Common metals include steel, aluminum, and copper. Local metal scrap yards or recyclers that accept metal materials are typically accessible. Metals are melted down and reformed into metal products. Markets are well established for metals. Figure 2.9 shows different types of metals are separated and arranged at demolition sites for recycling. For more information on recycling metal visit www.isri.org and www.recycle-steel.org (EPA, 2009B).

Figure 2.9: Different Types of Metals are Separated and Arranged at Demolition Sites for Recycling.

Source: (EPA, 2009B).

***Land Clearing Residuals, Soil and Rock*:** Trees and brushes removed from construction, renovation or demolition sites can be recycled as compost or mulch; and soil can be reused as fill and cover (EPA, 2009B). Figure 2.10 shows debris from trees, brushes and soil removed during site clearing.

Figure 2.10: Debris from Trees, Brushes and Soil Removed During Site Clearing.
Source: (EPA, 2009B).

***Concrete*:** Concrete is commonly recycled. It is crushed, the reinforcement bar is removed, and the material is screened for size. Market outlets for recycled concrete include road base, general fill, pavement aggregate, and drainage media (EPA, 2009B). Figure 2.11 shows concrete debris at a demolition site. For more information on recycling concrete visit www.concreterecycling.org.

Figure 2.11: Concrete Debris at a Demolition Site.
Source: (EPA, 2009B).

Asphalt Shingles: After the removal of nails, asphalt shingles can be ground and recycled into asphalt mixes. Figure 2.12 shows asphalt shingles piled up for recycling. For more information on recycling asphalt shingles, visit www.shinglerecycling.org (EPA, 2009B).

Figure 2.12: Asphalt Shingles Piled Up for Recycling.
Source: (EPA, 2009B)

Brick: Clean bricks are recycled by crushing the material. Market outlets for recycled brick include aggregate, drainage media, and general fill (EPA, 2009B). Figure 2.13 shows historical brick building under renovation.

Figure 2.13: Historical Brick Building under Renovation.
Source: (EPA, 2009B).

2.5.2 Effective Recycle Planning for C&D Waste

Effective recycling of C&D waste requires identification of recycling goals and objectives. The goals of recycling planning is to design optimal recycling techniques for processing C&D waste components into recycled materials with marketable or valuable end-use options at cost-effective rate; and thereby reducing the cost of C&D waste disposal, conserving resources, and protecting the environment by diverting C&D waste from landfills. To achieve these goals, it is necessary to determine the percentage of potential or estimated C&D waste components to be recycled. Some countries, states, counties or cities have regulations or ordinances that specify the percentage of C&D wastes or C&D waste components generated in the area that must be recycled. A realistic percentage can be arrived by considering all factors that affect C&D waste recycling in the area; be it city, state, region or country.

These goals can be achieved by enacting and enforcing regulations or ordinances that establish that any party or all the stakeholders that are involved in any activity that produces C&D wastes are responsible for the recycling of a certain percentage of the C&D wastes or C&D waste components they generated. First, the developer should be required to deposit a certain amount of money, depending on the estimated quantity of C&D wastes to be generated, before any permit is awarded for construction or demolition project. As such, the developer is obliged to inform the contractor that certain percentage of the C&D wastes generated by the project must be handled by C&D waste recycling facility designated in the area. Secondly, once the construction work has been completed, the developer must request a correct management certificate from the recycling facility. It must be demonstrated that the amount of wastes delivered by the developer is congruent with the estimate on which the deposit was based. The effective C&D wastes recycling management model, which can be implemented by the relevant government agency, is summarized in figure 2.14 as follows (Solís-Guzmán, et al., 2009) :

(i) Application for a building permit.

(ii) C&D waste evaluation report and deposition of money.

(iii) Developer informs the contractor that certain percentage of C&D waste generated must be handled by the designated recycling facility; through the contract specification.

(iv) Contractor removes and separate C&D waste components for recycling.

(v) C&D waste transported to C&D waste evaluation concession holder or recycling facility

(vi) Issuance of correct C&D management certificate to the developer by the C&D waste concession holder.

(vii) Finally, the return of the monetary deposit to the developer following the tendering of the correct C&D management certificate.

In this thesis, it was assumed that the steps described above would be enforced by the relevant government agency in the geographical area considered in this study. Also, Government can encourage participation and investment in C&D waste recycling through tax credit or grant for investment in C&D waste recycling facilities and higher tax on C&D waste disposal into landfills.

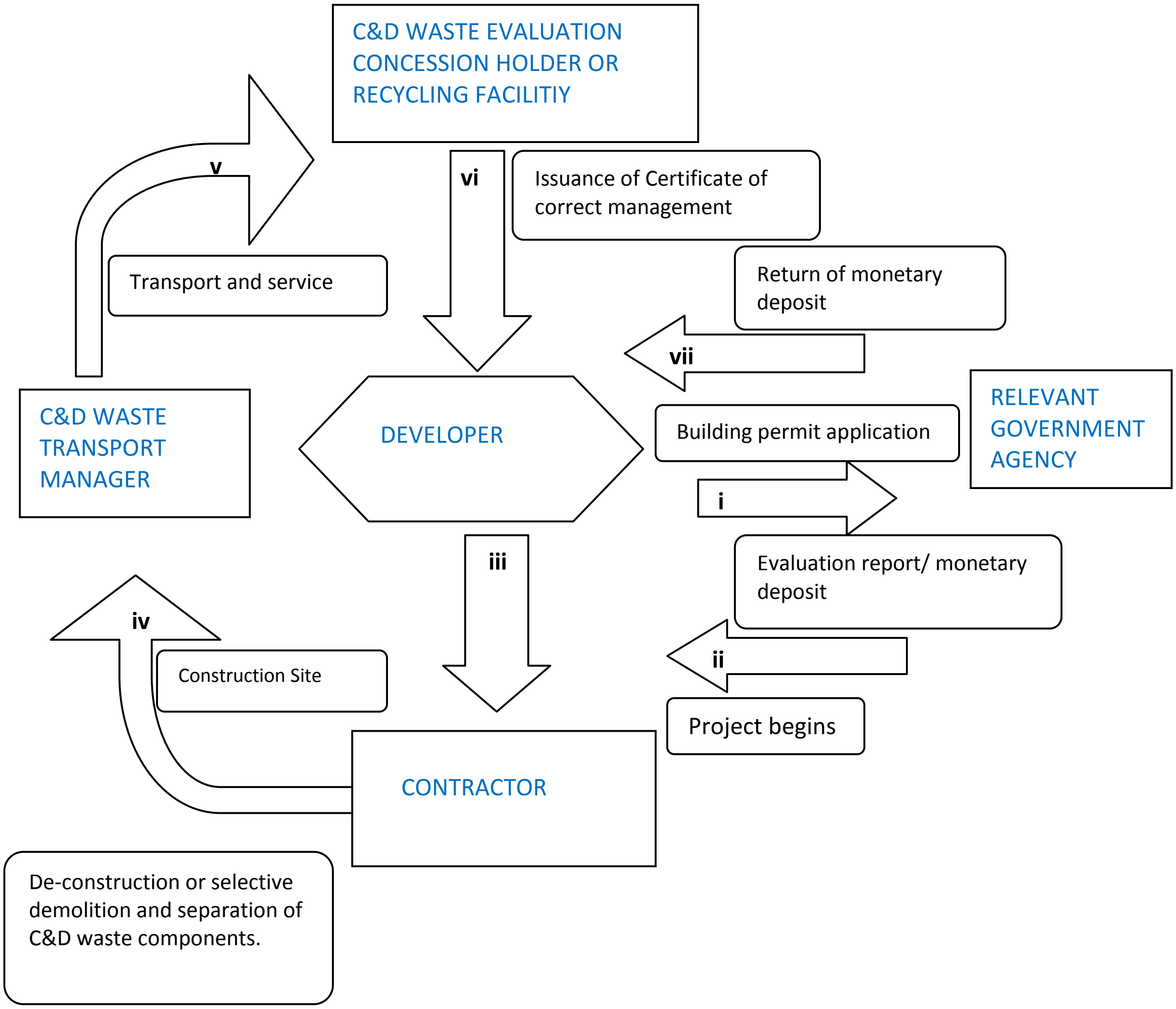


Figure 2.14: Effective C&D Waste Management Model That Can be Implemented in a Geographical Area by the Relevant Government Agency.
Source: (Solís-Guzmán, J. et al.,2009).

2.5.3 Factors That Affect Effective C&D Waste Recycling

The factors that affect effective recycling of C&D wastes in a particular area are as follows:

(i) C&D waste regulations in the country, state, county or city.

(ii) Available active recycling facilities in the area and their tipping fees.

(iii) Available active C&D landfills in the area and their tipping fees.

(iv) Availability of market for end-use options for C&D recycled materials.

(v) Quantity of recyclable C&D waste components generated in the area.

(vi) The cost of transporting C&D waste components from construction, renovation or demolition site to recycling facilities.

(vii) The cost of loading and unloading C&D waste components in the area.

(viii) The distance, traffic condition and travel time between C&D waste components generation sites or locations and the recycling facilities locations or centers.

(ix) The cost of recycling each component of C&D wastes to available end-use options.

(x) The price of each end-use option for the recycled C&D waste components.

(xi) The monetary profits from C&D waste recycling; comparing the difference between the cost of recycling the C&D waste and the income accruable from selling the recycled materials for the end-use options.

(xii) The economic, environmental and even social benefits of recycling C&D waste in the area.

(xiii) Government incentives and involvement in promoting or supporting effective C&D waste recycling in the area.

2.5.4 Benefits of Effective C&D Waste Recycling

United States Environmental Protection Agency (EPA) recognizes the following economic, environmental and social benefits of C&D waste recycling (EPA, 2009B):

(i) It reduces the production of greenhouse gas emissions and other pollutants by reducing the need to extract raw materials and shipping new materials long distances.

(ii) It conserves landfill space, reduces the need for new landfills and their associated cost.

(iii) It saves energy and reduces the environmental impact of producing new materials by reducing extraction and manufacturing processes.

(iv) It creates employment opportunities and economic activities in recycling industries.

(v) It saves money by reducing project disposal costs, transportation costs, and the cost of some new construction materials by recycling old materials (EPA, 2009B).

2.6 Mathematical Model

A mathematical model uses mathematical language to describe a system or event. Mathematical models are used not only in the natural sciences and engineering disciplines, but also in social sciences. Eykhoff (1974) defined a mathematical model as 'a representation of the essential aspects of an existing or a system to be constructed which presents knowledge of that system in usable form'. Mathematical models can take many forms, including but not limited to, a dynamical system, statistical models, differential equations, or game theoretic models. These and other types of models can overlap, with a given model involving a variety of abstract structures (Wikipedia, 2009).

2.7 Previous Related Work

(a) Case Studies of Successful Construction and Demolition Waste Recycling

(i) Detroit, MI: In December 2005, the cleanup of a two-acre former automotive property in Detroit, Michigan was made possible through the leadership of a local nonprofit organization and funding assistance provided by EPA, in-kind services, and C&D waste recycling activities.

Working within a tight budget, Focus: HOPE Revitalization conducted demolition and cleanup activities on the Brownfields property for its intended reuse as a parking lot for a planned mixed-use development on the adjacent property. Largely, the C&D waste recycling activities made the project feasible by reducing the total project cost by 20 percent, a savings of $150,000, through the recycling of approximately 1,200 tons of materials and over 13,000 gallons of waste water. As a result, the property's reuse provided a catalyst to revitalization in the surrounding neighborhood. For more information on this project, please visit: www.epa.gov/brownfields/success/Detroit_MI_Success_012808.pdf (EPA, 2009B).

(ii) Emeryville, CA*:* In July 2003, the City of Emeryville provided $1,175,000 in EPA Brownfields Revolving Loan funds to GreenCity LLC to assist with cleanup costs associated with the GreenCity Lofts property, a former paint factory. The GreenCity Lofts project team completed cleanup of the 0.9-acre property in December 2004 and 62 condominiums were constructed in 2005. Demolition of the former paint factory and warehouse buildings was necessary before construction of the lofts could begin. The project team employed C&D waste recycling practices including deconstructing (hand dismantling) the buildings on the former industrial property as an alternative to traditional demolition. As a result, 94.6 percent of the demolition waste was recycled, exceeding the nearby City of Oakland's legal requirement by 45 percent. In addition, 21,569 tons of excavated soil was diverted from disposal and used as Beneficial Cover at a local Class II Landfill reducing project cost by an estimated $496,708 in eliminated tipping fees. For more information on this project, please visit: *www.epa.gov/brownfields/success/emeryvilleca_cd_ss_final.pdf* (EPA, 2009B).

(iii) Richmond, VA: The former Lucent Richmond Works facility, a 120-acre RCRA facility, was fenced off and left idle, leaving behind over 700,000 square feet of old and dilapidated manufacturing buildings. With coordination between the developer, the previous site owner, EPA, and the Virginia Department of Environmental Quality, the property is being revitalized into *The Shops of White Oak Village,* a development that will feature several restaurants, a hotel, national retail stores, and several regional and local specialty shops. After demolishing the existing onsite buildings, the developer diverted 84,500 tons of material from landfills, achieving a 93 percent overall recycling rate. According to the project's demolition contractor, the amount of materials diverted from landfills could have filled two Richmond Coliseums. Cost-savings associated with recycling and reuse of demolition materials are estimated to be approximately $3.6 million. For more information on this project, please visit:

www.epa.gov/reg3wcmd/ca/va/pdf/vad066000993.pdf (EPA, 2009B).

However, these case studies only proved that recycling C&D wastes is more often cost-effective than disposal at landfills, but there was no model developed for detailed estimation of the cost of recycling C&D waste components in a geographical area; as compared to the revenue that would be derived from selling the recycled materials for end-use options.

(b) Database System Application for Cost-Effective C&D Waste Management

Udo-Inyang and Arsankan (2003) developed a database application that helped contractors or construction managers to decide on the disposal method with minimum cost for C&D wastes in New Jersey State in United States. The application program was used to calculate and compare the possible minimum costs of source separating and sending the C&D wastes to a recycling facility, with the disposal of C&D wastes to a landfill or transfer station. Microsoft Access was used as the database management system, and Visual Basic 6.0 was used as the programming language for the application.

An input screen was designed for the user to enter the project location, material types and quantities, loading type, truck capacity, and project duration. The program calculated the cost alternatives by using these inputs and integrating them with the data stored in the system. The data used in conducting the research were obtained from New Jersey Department of Environmental Protection. The database system was expected to benefit contractors and construction managers by enabling them to save time searching for data, prevent cost increases that may occur due to lack of knowledge, and encourage them to recycle C&D wastes by demonstrating that disposal of C&D waste to landfills is not always the cost-effective way of waste management (Arsankan, 2003). However, this database application system only calculates and compares the alternatives cost of disposing the C&D wastes at landfills or recycling facilities, it does not consider the cost of recycling the C&D waste in a geographical area and the market for the recycled material end-use options.

(c) Models for Construction and Demolition Waste Management

Solís-Guzmán, et al. (2009) developed a C&D waste quantification model to help all construction stakeholders or participants in Spain in planning, implementation and control of C&D wastes through prevention, reuse and recycling; by studying 100 dwelling projects in Spain, especially their bill of quantities, and defining three coefficients to estimate the demolished volume (CT), the wreckage volume (CR) and packaging volume (CE). The model has been tested at the Los Alcores Community treatment plants for the last two years and has proved to be ninety five percent (95%) accurate in its predictions.

The estimation of the C&D wastes volume that would be generated would then enable the calculation of the deposit that the building developer must pay and the control of the disposal of the C&D wastes. The building developer would recuperate this deposit only if he or she disposes of the C&D wastes generated on the building site in a proper way, and demonstrates this by presenting the certificates issued by the authorized treatment facilities. This model and the methodology to determine the waste volume can be exported to other places in order to foster correct C&D waste management. According to Solís-Guzmán, for different world regions, the coefficients that enable the estimation of the three waste streams (demolition, wreckage and packaging) differ only slightly from those defined in Spain since material dimensions, packaging systems and construction solutions are standardized in many countries and are very similar to those used in Spain. The main difference is that new dwelling types need to be added to the present model. This possibility is currently being evaluated in order to implement the quantification method in the United Kingdom (Solís-Guzmán, et al., 2009). As discussed above, the model only deals with quantification of C&D wastes to be generated and the percentage to be recycled, it does not, however, consider the cost of recycling the C&D wastes in a geographical area and the market for the recycled material end-use options.

Also, Spengler, et al. (1994) developed a model for integrated dismantling and recycling planning. A sophisticated mixed integer linear programming model was formulated. Different solution procedures were analyzed and due to high complexity of the planning problem, a heuristic decomposition algorithm was developed. The limitation of this model is that it only considers the cost of dismantling C&D waste components and the proceeds from recycling C&D waste components by reuse options, but does not consider in detail the cost of recycling the C&D wastes components to end-use options.

In addition, Hao , et al. (2007) developed a simulation model using system dynamic method for construction and demolition waste management in Hong Kong by incorporating the relationship of major activities inherently involved in C&D waste management. The model have the potential to assist decision makers and practitioners to better understand the complexity of information and process involved in managing C&D wastes throughout a project's life-cycle.

The simulation shows how life-span of landfills in a geographical area could be extended and the cost of disposing C&D wastes could be reduced through factors such as environmental consciousness, legislations that promote reduction of C&D wastes right from the design, procurement and construction phases and taxation on C&D waste disposal on landfill, availability of recycle facilities and reduced cost of disposing on-site separated C&D to recycle facilities instead of direct disposal to landfills, and profit from selling reuse components of C&D wastes directly. However, the simulation model does not consider the cost of recycling the C&D wastes in a geographical area and the market for the recycled materials end-use options.

(d) Characterization, Composition and Quantity of Construction and Demolition Wastes

Kourmpanis, et al. (2008) categorized C&D wastes depending on their origin. It included C&D wastes arising from the total or partial demolition of buildings and/or civil infrastructure; wastes arising from construction of buildings and/or civil infrastructure; soil, rocks and vegetation arising from land leveling, excavation, civil works and /or general foundations. They also identified that the parameters that influence the qualitative characteristics of C&D wastes are the period of construction, main materials used for the construction of a building, techniques that are applied for the demolition of a building, and the historical, cultural, economic value and importance of a building. In addition, the study showed the composition of C&D wastes in European countries. The study also used an indicative mathematical model for estimation of generated quantities of C&D waste developed by National Technical University of Athens for calculating the quantities of C&D waste generated. Finally, the study recognized that the selection of optimum management scheme regarding C&D waste is a complex decision-making problem, and identified the main issues that have to be taken into consideration to solve this problem.

Furthermore, Camp, Dresser and McKee Inc. (1998) studied the quantity and composition of construction and demolition debris in Wisconsin, and identified the largest materials in the commercial construction waste stream, residential construction waste stream, commercial demolition waste stream and residential demolition waste stream.

Finally, Cascadia Consulting Group (2006) conducted a study on detailed characterization of construction and demolition wastes for California Environmental Protection Agency. The study presented an overview of California's C&D waste stream by subsector in 2005. The subsectors considered were new residential construction (10%), new non-residential construction (8%), residential remodel (19%), non-residential remodel (11%), demolition (21%), roofing (14%) and other C&D wastes (17%). The study also presented an overview of C&D waste divertibility in four metropolitan areas of California in 2005. The components included recyclable aggregates (27%), recyclable wood (15%), recyclable metal (4%), other recoverable material (20%), rock, dirt and sand (8%), and other municipal solid waste (26%).

None of the studies, however, considered the cost of recycling the components of C&D wastes and the tool for estimating the revenue that would be gotten from selling the recycled materials for the available end-use options.

(e) End-use Options and Market for Recycled Materials

United States Environmental Protection Agency (EPA, 2009B) conducted several case studies, and identified various end-use options and available market for different components of C&D waste in United States. Several end-use options for components such as wood, gypsum wallboard or drywall, asphalt paving, land clearing residuals, metals, concrete, brick, asphalt shingles and non-asphalt shingles were identified in the case studies. However, the case studies did not provide any tool for estimating the potential cost of recycling each of the C&D waste components into the recycled materials or end-use options. The study did not also provide any tool for estimating the potential revenue that would be generated by selling the recycled materials from the recyclable C&D waste components.

(f) Construction and Demolition Landfills, Environmental Pollution and Greenhouse Gas Emissions

ICF Incorporated (1995) conducted a study on construction and demolition waste landfills for United States Environmental Protection Agency (EPA) by extracting leachate data for analysis from several C&D waste landfills across United States. Leachate sampling data from twenty one (21) landfills in United States were used to develop a C&D landfill leachate database. The database contains sampling data for total of three hundred and five (305) parameters analyzed for at least once in any of the landfills.

Based on the number of landfills at which the benchmark was exceeded and a comparison between the median detected concentration and the benchmark, seven parameters which emerged as being potentially problematic are as follows: 1, 2-dichloroethane (organic), methylene chloride (organic), cadmium (inorganic), iron (inorganic), lead (inorganic), manganese (conventional parameter) and total dissolved solids, TDS (conventional parameters). For iron, manganese and TDS, the benchmarks were Secondary Maximum Contaminants Levels (SMCLs), which are set to protect water supplies for aesthetic reasons. For example, to maintain pleasant taste, rather than for health-based reasons. None of the remaining four parameters exceeded its benchmark by factor of 10 or more; indicating that concentrations in ground water where ground-water monitoring or drinking water wells may be located were likely to fall below the health-based benchmarks (ICF Incorporated, 1995).

Moreover, Staley and Morton (2008) conducted a research on composition of municipal solid waste in the United States and implications for carbon sequestration and methane yield. Eleven statewide waste characterization studies were compared to assess variation in the quantity and composition of waste after separation of recyclable and compostable materials; that is discarded waste. These data were used to assess the impact of varying composition on sequestered carbon and methane yield (Staley and Morton, 2008).

Finally, Delaware Valley Regional Planning Commission, DVRPC, (2009) carried out a greenhouse gas inventory by identifying activities that are responsible for greenhouse emissions, ascertaining the level of each activity, and then calculating the associated greenhouse gas emissions. The study showed that in 2005, gross emissions of greenhouse gases within the DVRPC planning region totaled 90.3 million metric tons of carbon dioxide equivalent ($MMTCO_2E$). It was shown that landfill methane contributed 1.88 million metric tons of carbon dioxide equivalent ($MMTCO_2E$) to the total sum. The inventory can help in identifying the greatest sources of greenhouse gas emissions within a particular geographic region or area, understanding emission trends, quantifying the benefits of activities that reduce emissions, establishing a basis for developing an action plan, tracking progress in reducing emissions, and setting goals and targets for future reduction of greenhouse emissions (DVRPC, 2009).

2.8 Observations and Remarks

There have been several studies or researches conducted on construction and demolition waste; in terms of C&D generation, characterization, estimation of quantity, reduction, recovery, reuse, recycling, disposal. Also, many studies have identified the environmental impacts of C&D disposal in landfills, the economic and environmental benefits of recovering, reusing and recycling C&D wastes. Most of these studies evaluated the progress and achievements of C&D waste management in terms of tons or percentage diverted to recycling facilities or landfills, tons or percentage reuse or sold directly and the proceeds, and concluded that it is cost-effective to reuse or recycle C&D waste than disposing into landfills.

However, these previous studies paid little or no attention to detailed cost of recycling C&D waste in a particular geographical area or region as compared to the monetary value (dollar value) of selling the recycled materials to available end users. Many models are developed to quantify the potential waste to be generated and comparing the alternative cost of disposal at landfills or recycling facilities; without models for evaluating the potential cost of recycling the C&D waste components in a geographical area or region into marketable end-use options and the potential proceeds from selling the end-use options. As such, the previous studies only paid attention to generation and diversion of C&D wastes from landfills to recycling facilities, with little or no attention to the processing of the C&D components to end-use options and developing market for the recycled materials in their geographical region or area.

Thus, the purpose of this study was to develop a mathematical model that can help stakeholders in construction business, including developers, contractors, construction managers and government, to evaluate the potential cost of recycling C&D waste components in their geographical area or region, and the potential proceeds from the recycled materials. This model would enable the stakeholders in construction industry to effectively plan for the recycling C&D waste components in their geographical area or region; by helping them to identify C&D waste components that their recycling would yield good profits and those that their recycling would yield less or no profit in the geographical region or area.

Hence, private companies or individuals can invest and participate in recycling of C&D waste components that yield good profits in their region or area. The Government can then sponsor or provide incentives for the recycling of C&D waste components that yield no or less profit in order to reduce environmental pollution and generate jobs in their geographical area or region. As such, the stakeholders in construction industry would be encouraged to participate, invest and promote recycling of C&D wastes properly; leading to reduction in construction or demolition cost, conservation of resources, creation of employment, and other economic and environmental benefits.

This study considered factors such as the tipping fees charged at recycling facilities, cost of recycling the recyclable components to recycled materials with market value, and the price or market value of the recycled materials. It also considers the percentage of the total quantity of particular C&D waste components that is recycled to particular recycled materials or end-use options.

CHAPTER 3

METHODOLOGY

3.1 Introduction

The objective of this study is to develop a mathematical model that can help stakeholders in construction business, including developers, contractors, construction managers and government, to evaluate the potential cost of recycling C&D waste components generated in their geographical area or region, and the potential monetary proceeds from the recycled materials. Since previous studies recommended that it is cost-effective to recycle C&D waste components than disposing them at landfills, the cost of recycling various recyclable components of C&D waste would be evaluated and the monetary proceeds from selling the recycled materials would be evaluated.

The mathematical model would be developed to compare the estimated monetary cost of recycling the recyclable components of C&D wastes with the estimated monetary revenue that would be obtained from selling the recycled materials, thereby calculating the monetary profits of the C&D wastes recycling. The result would assist the stakeholders in construction industry in identifying C&D waste components whose recycling would yield good profits and those that their recycling would yield less or no profit in their geographical areas. Based on the result, private companies or individuals can invest and participate in recycling C&D waste components whose recycling yield good profit in their respective areas. Then government can sponsor or support the recycling of C&D waste components whose recycling yield little or no profit in order to prevent environmental pollution and generate employment opportunities in their geographical areas or regions. Stakeholders in construction industry, thus, would be able to participate, invest and promote the recycling of C&D wastes properly.

3.2 Data

The data required in conducting this research was collected from relevant agencies and establishments. The data was used in testing the effectiveness of the mathematical model. Since the regulations guiding the recycling of C&D waste varies from state to state, county to county or city to city, there is need to limit this research to a definite area. The data required in conducting this research are as follows:

1. The list and locations of existing C&D waste recycling facilities in Pennsylvania, and the tipping fees that they charge for different components of C&D waste disposal.
2. The recycled materials from C&D waste components.
3. The sale price of each of the recycled materials from C&D waste components.
4. The cost of recycling each component of C&D wastes to available end-use options.
5. The quantity of each recyclable C&D waste components generated in the geographical area considered in this study.

3.2.1 The Quantity of C&D Waste Components Generated in Pennsylvania and Their Locations

The estimated quantity of C&D wastes disposed in Pennsylvania in 2009 is obtained from Pennsylvania Department of Environmental Protection (PADEP) electronic database. The database showed the quantity of C&D wastes disposed at each of the sixty seven (67) counties in Pennsylvania. The sum of the quantities disposed in Pennsylvania in 2009 by the 67 counties is equal to 1,070,165.2 tons. Based on the total quantity disposed in the state in 2009, the percentage of C&D wastes disposed 2009 in each of the 67 counties are estimated. The estimated annual quantity of construction and demolition wastes disposed in Pennsylvania in 2009, and the percentage disposed at each of the 67 counties in Pennsylvania are shown in appendix C.

The top five counties with higher quantity of C&D wastes disposal in Pennsylvania in 2009 are: Allegheny County with 16.9% (180,863 tons) of the total annual quantity (1,070,165.2 tons) disposed, Montgomery County with 7.9% (85,006 tons) of the total annual quantity (1,070,165.2 tons) disposed, Chester County with 7.7% (82,556.4 tons) of the total annual quantity (1,070,165.2 tons) disposed, Lancaster County with 6.3% (66,960.8 tons) of the total annual quantity (1,070,165.2 tons) disposed, and Philadelphia County with 5.3% (56,577 tons) of the total annual quantity (1,070,165.2 tons) disposed in Pennsylvania in 2009.

Meanwhile, it is worth noting that Pennsylvania Department of Environmental Protection (PADEP) does not keep a comprehensive record of the quantities of C&D wastes disposed at recycling facilities or energy recovery facilities; it only keeps a comprehensive record of the quantities of C&D wastes disposed at landfills. As such, the quantities of C&D wastes considered above are the quantities disposed mostly at landfills in 2009.

Some counties that generated higher quantity of C&D wastes may have disposed a percentage lower than the total quantity generated; if there is a lot of recycling activities going on in the county. For instance, the 5.3% (56,577 tons) disposal in Philadelphia in 2009 may have been much lower than the actual C&D wastes quantity generated in Philadelphia that year. This is based on the assumption that many of the C&D wastes generated may have been recycled since there is a lot of C&D wastes recycling activities in Philadelphia due to the presence of many C&D recycling companies in the county.

3.2.2 C&D Waste Components and Composition in Pennsylvania

Due to insufficient records or data on the composition or fraction of C&D waste components in Pennsylvania, the estimated C&D waste component fraction in Lancaster County, published by Lancaster County Solid Waste Management Authority (LCSWMA), is adopted for entire Pennsylvania in this study. Table 3.1 shows the estimated percentages of C&D waste components in Lancaster, published by Lancaster County

Solid Waste Management Authority (LCSWMA). Figure 3.1 is the graphical presentation of the estimated C&D waste components fractions.

According to table 3.1 or figure 3.1, Wood has the highest fraction of 25.6% of the total weight; followed by roofing shingles with 18.0%; concrete/brick/block/dirt/ asphalt combined has 17.8%; drywall/plaster has 13.2%; all metals combined has 2.6%; and non-ferrous metals (aluminum in particular) has 0.2% . The fractions (in percentage) are used in estimating the quantity of individual C&D component disposed in Pennsylvania in general, and the quantity of each C&D waste component disposed in Allegheny County, Montgomery County, Chester County, Lancaster and Philadelphia County in particular in 2009.

Based on the above assumptions and calculations, the estimated quantity of each C&D waste component disposed in entire Pennsylvania in 2009 is shown in table 3.2. In addition, the estimated quantity of each component of C&D wastes disposed in Allegheny County, Montgomery County, Chester County, Lancaster and Philadelphia County in 2009 are shown in table 3.3, table 3.4, table 3.5, table 3.6 and table 3.7 respectively.

Corrugated containers with 1.6% of the total weight and other materials (fiberglass, plastics, porcelain, carpet, linoleum, unspecified) with 20.9% of the total weight are not considered in this study. Similarly, only non-ferrous metals are considered in this study;

since steel recycling has already been a highly profitable business with many recycling facilities and great market for the recycled steels for a long time.

Table 3.1: C&D Waste Component Fraction in Lancaster County.

Waste Component	**Fraction of Transfer Station Volume**	**Fraction of Landfill Station Volume**	**Approximate Fraction by Total Volume**	**Approximate Fraction by Total Weight**
Asphalt	1.1%	0.2%		
Concrete/Brick/Block	2.4%	2.8%		
Dirt	1.7%	0.6%		
Concrete/Brick/Block/Dirt/Asphalt -Combined	**5.2%**	**3.6%**	**4.6%**	**17.8%**
Ferrous Metals - Including Unspecified	**8.0%**	**6.5%**	**7.4%**	**2.6%**
Copper, Brass, etc.	**0.0%**	**0.0%**	**0.0%**	**0.0%**
Aluminum	**0.1%**	**1.5%**	**0.7%**	**0.2%**
Metals-Combined	**8.1%**	**8.0%**	**8.1%**	**2.8%**
Wood (unspecified)	11.9%	0.1%		
Wood, untreated	14.4%	24.8%		
Wood, treated, painted	4.9%	2.1%		
Wood - Combined	**31.2%**	**27.0%**	**29.5%**	**25.6%**
Drywall/Plaster	**13.6%**	**10.6%**	**12.5%**	**13.2%**
Corrugated Containers	**8.6%**	**0.6%**	**5.6%**	**1.6%**
Roofing Shingles	**15.8%**	**12.5%**	**14.6%**	**18.0%**
Other - Combined (fiberglass, plastic, porcelain, carpet, linoleum, unspecified)	**17.6%**	**37.6%**	**25.3%**	**20.9%**
Total (not equal to 100% due to rounding)	**100.1%**	**99.9%**	**100.2%**	**99.9%**

Source: Lancaster County Solid Waste Management Authority (www.lcswma.org/documents/AppendixA.pdf), 1999.

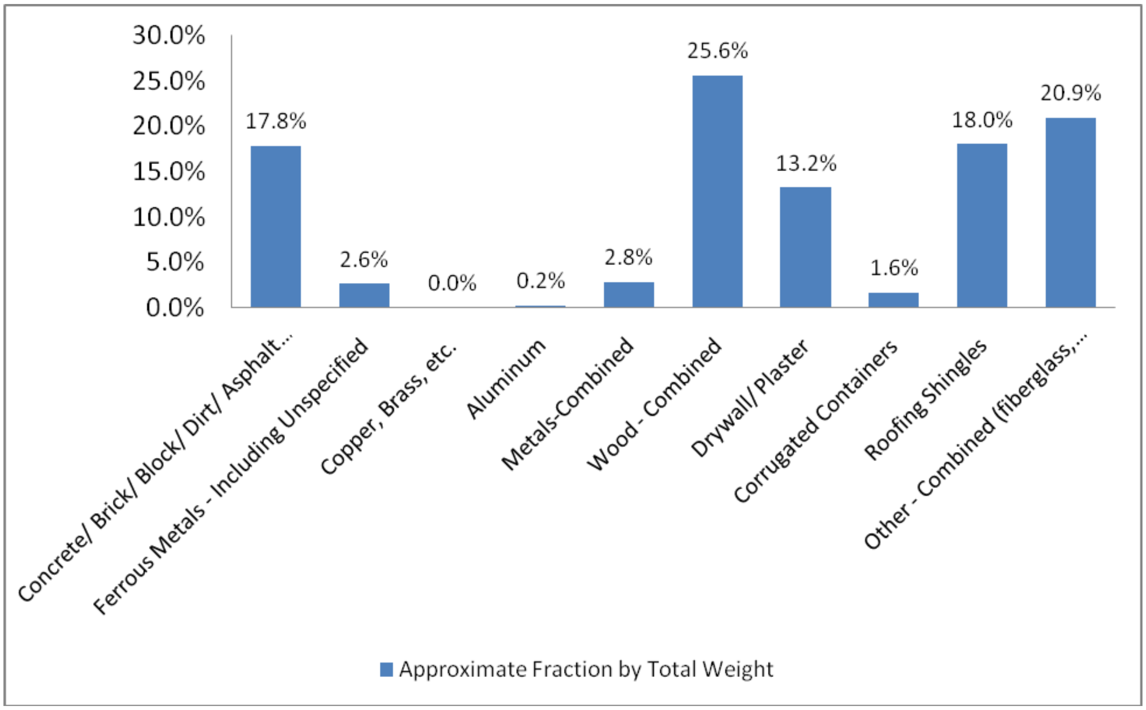


Figure 3.1: Approximate Fraction of C&D Components in Lancaster County by Total Weight.

Source: Lancaster County Solid Waste Management Authority, LCSWMA, (www.lcswma.org/documents/AppendixA.pdf), 1999.

Table 3.2: Estimated Quantity of C&D Waste Components Disposed in Pennsylvania in 2009 (Based on The Fractions of C&D Waste Components in Lancaster).		
*BASED ON ESTIMATED TOTAL QUANTITY OF C&D WASTES DISPOSED IN PENNSYLVANIA IN 2009 =1,070,165.2 TON.		
Waste Component	**Approximate Fraction by Total Weight**	**Quantity of C&D Disposed in Ton**
Asphalt		
Concrete/Brick/Block		
Dirt		
Concrete/ Brick/ Block/ Dirt/ Asphalt -Combined	**17.8%**	**190489.4**
Ferrous Metals - Including Unspecified	**2.6%**	**27824.3**
Copper, Brass, etc.	**0.0%**	**0.0**
Aluminum	**0.2%**	**2140.3**
Metals-Combined	**2.8%**	**29964.6**
Wood (unspecified)		
Wood, untreated		
Wood, treated, painted		
Wood - Combined	**25.6%**	**273962.3**
Drywall/ Plaster	**13.2%**	**141261.8**
Corrugated Containers	**1.6%**	**17122.6**
Roofing Shingles	**18.0%**	**192629.7**
Other - Combined (fiberglass, plastic, porcelain, carpet, linoleum, unspecified)	**20.9%**	**223664.5**
Total (not equal to 100% due to rounding)	**99.9%**	**1069095.0**

*Source: PADEP 2010
(http://www.portal.state.pa.us/portal/server.pt?open=514&objID=589667&mode=2)

Table 3.3: Estimated Annual Quantity of C&D Waste Components Disposed in Allegheny County in 2009 (Based on The Fractions of C&D Waste Components in Lancaster).		
*BASED ON ESTIMATED TOTAL QUANTITY OF C&D WASTES DISPOSED IN ALLEGHENY IN 2009 =180,863 TON.		
Waste Component	**Approximate Fraction by Total Weight**	**Quantity of C&D Disposed in Tons**
Asphalt		
Concrete/Brick/Block		
Dirt		
Concrete/Brick/Block/Dirt/Asphalt -Combined	**17.8%**	**32193.6**
Ferrous Metals - Including Unspecified	**2.6%**	**4702.4**
Copper, Brass, etc.	**0.0%**	**0.0**
Aluminum	**0.2%**	**361.7**
Metals-Combined	**2.8%**	**5064.2**
Wood (unspecified)		
Wood, untreated		
Wood, treated, painted		
Wood - Combined	**25.6%**	**46300.9**
Drywall/Plaster	**13.2%**	**23873.9**
Corrugated Containers	**1.6%**	**2893.8**
Roofing Shingles	**18.0%**	**32555.3**
Other - Combined (fiberglass, plastic, porcelain, carpet, linoleum, unspecified)	**20.9%**	**37800.4**
Total (not equal to 100% due to rounding)	**99.9%**	**180682.1**

*Source: PADEP 2010 (http://www.portal.state.pa.us/portal/server.pt?open=514&objID=589667&mode=2)

Table 3.4: Estimated Annual Quantity of C&D Waste Components Disposed in Montgomery County in 2009 (Based on The Fractions of C&D Waste Components in Lancaster).		
*BASED ON ESTIMATED TOTAL QUANTITY OF C&D WASTES DISPOSED IN MONTGOMERY IN 2009 =85,006 TON.		
Waste Component	**Approximate Fraction by Total Weight**	**Quantity of C&D Disposed in Tons**
Asphalt		
Concrete/Brick/Block		
Dirt		
Concrete/Brick/Block/Dirt/Asphalt -Combined	**17.8%**	**15131.1**
Ferrous Metals - Including Unspecified	**2.6%**	**2210.2**
Copper, Brass, etc.	**0.0%**	**0.0**
Aluminum	**0.2%**	**170.0**
Metals-Combined	**2.8%**	**2380.2**
Wood (unspecified)		
Wood, untreated		
Wood, treated, painted		
Wood - Combined	**25.6%**	**21761.5**
Drywall/Plaster	**13.2%**	**11220.8**
Corrugated Containers	**1.6%**	**1360.1**
Roofing Shingles	**18.0%**	**15301.1**
Other - Combined (fiberglass, plastic, porcelain, carpet, linoleum, unspecified)	**20.9%**	**17766.3**
Total (not equal to 100% due to rounding)	**99.9%**	**84921.0**

*Source: PADEP 2010 (http://www.portal.state.pa.us/portal/server.pt?open=514&objID=589667&mode=2)

Table3.5: Estimated Annual Quantity of C&D Waste Components Disposed in Chester County in 2009 (Based On The Fractions of C&D Waste Components in Lancaster).		
*BASED ON ESTIMATED TOTAL QUANTITY OF C&D WASTES DISPOSED IN CHESTER IN 2009 =82,556.4 TON.		
Waste Component	**Approximate Fraction by Total Weight**	**Quantity of C&D Disposed in Tons**
Asphalt		
Concrete/Brick/Block		
Dirt		
Concrete/Brick/Block/Dirt/Asphalt - Combined	**17.8%**	**14695.0**
Ferrous Metals - Including Unspecified	**2.6%**	**2146.5**
Copper, Brass, etc.	**0.0%**	**0.0**
Aluminum	**0.2%**	**165.1**
Metals-Combined	**2.8%**	**2311.6**
Wood (unspecified)		
Wood, untreated		
Wood, treated, painted		
Wood - Combined	**25.6%**	**21134.4**
Drywall/Plaster	**13.2%**	**10897.4**
Corrugated Containers	**1.6%**	**1320.9**
Roofing Shingles	**18.0%**	**14860.2**
Other - Combined (fiberglass, plastic, porcelain, carpet, linoleum, unspecified)	**20.9%**	**17254.3**
Total (not equal to 100% due to rounding)	**99.9%**	**82473.8**

*Source: PADEP 2010
(http://www.portal.state.pa.us/portal/server.pt?open=514&objID=589667&mode=2.

Table 3.6: Estimated Annual Quantity of C&D Waste Components Disposed in Lancaster County in 2009 (Based on The Fractions of C&D Waste Components in Lancaster).		
*BASED ON ESTIMATED TOTAL QUANTITY OF C&D WASTES DISPOSED IN LANCASTER IN 2009 =66,960.8 TON.		
Waste Component	**Approximate Fraction by Total Weight**	**Quantity of C&D Disposed in Tons**
Asphalt		
Concrete/Brick/Block		
Dirt		
Concrete/Brick/Block/Dirt/Asphalt - Combined	**17.8%**	**11919.0**
Ferrous Metals - Including Unspecified	**2.6%**	**1741.0**
Copper, Brass, etc.	**0.0%**	**0.0**
Aluminum	**0.2%**	**133.9**
Metals-Combined	**2.8%**	**1874.9**
Wood (unspecified)		
Wood, untreated		
Wood, treated, painted		
Wood - Combined	**25.6%**	**17142.0**
Drywall/Plaster	**13.2%**	**8838.8**
Corrugated Containers	**1.6%**	**1071.4**
Roofing Shingles	**18.0%**	**12052.9**
Other - Combined (fiberglass, plastic, porcelain, carpet, linoleum, unspecified)	**20.9%**	**13994.8**
Total (not equal to 100% due to rounding)	**99.9%**	**66893.8**

*Source: PADEP 2010 (http://www.portal.state.pa.us/portal/server.pt?open=514&objID=589667&mode=2.

Table 3.7: Estimated Annual Quantity of C&D Waste Components Disposed in Philadelphia County in 2009 (Based on The Fractions of C&D Waste Components in Lancaster).		
*BASED ON ESTIMATED TOTAL QUANTITY OF C&D WASTES DISPOSED IN PHILADELPHIA IN 2009 =56,577 TON.		
Waste Component	**Approximate Fraction by Total Weight**	**Quantity of C&D Disposed in Tons**
Asphalt		
Concrete/Brick/Block		
Dirt		
Concrete/Brick/Block/Dirt/Asphalt -Combined	**17.8%**	**10070.7**
Ferrous Metals - Including Unspecified	**2.6%**	**1471.0**
Copper, Brass, etc.	**0.0%**	**0.0**
Aluminum	**0.2%**	**113.2**
Metals-Combined	**2.8%**	**1584.2**
Wood (unspecified)		
Wood, untreated		
Wood, treated, painted		
Wood - Combined	**25.6%**	**14483.7**
Drywall/Plaster	**13.2%**	**7468.2**
Corrugated Containers	**1.6%**	**905.2**
Roofing Shingles	**18.0%**	**10183.9**
Other - Combined (fiberglass, plastic, porcelain, carpet, linoleum, unspecified)	**20.9%**	**11824.6**
Total (not equal to 100% due to rounding)	**99.9%**	**56520.4**

*Source: PADEP 2010
(http://www.portal.state.pa.us/portal/server.pt?open=514&objID=589667&mode=2.

3.2.3 Active C&D Waste Components Recycling Facilities in Pennsylvania

The names, addresses and contacts of C&D waste recycling facilities in Pennsylvania were obtained from Pennsylvania Department of Environmental Protection (PADEP) electronic or internet database. The C&D waste recycling facilities were contacted through electronic mails and phone calls for information on C&D waste recycling in Pennsylvania. Many of the C&D wastes recycling facilities contacted were reluctant to release information for this research.

The few C&D wastes recycling facilities that provided data for this study did so through electronic mails. The C&D wastes recycling facilities that provided data for this study are as follows: Winzinger Recycling, Delaware & Allegheny Ave., Philadelphia; USA Gypsum, Texter Mountain Road, Reinholds; Miller's Wood Recycling, Industrial Park Road, Lewistown; David Geppert Recycling, Inc., Wayne Ave., Philadelphia; Appendix A shows the end user type of demolition and construction wastes recycling facilities in Pennsylvania. Also, the data on C&D wastes recycling obtained from some C&D waste recyclers in Pennsylvania and sources are documented in appendix B.

3.2.4 Tipping Fees Charged at Recycling Facilities in Pennsylvania

Information on the tipping fees charged at recycling facilities was obtained from different C&D waste recycling facilities in Pennsylvania and US Environmental Protection

Agency (EPA) publication. The average tipping fees are estimated as shown in appendix D. The estimated average tipping fee for disposing asphalt/concrete/block/brick-combined is $2.00 per ton. The estimated average tipping fees for disposing wood, drywall and roofing shingles are $31.00, $25.00 and $47.00 respectively. No tipping fee is charged for disposing metal scraps.

3.2.5 The Cost of Recycling C&D Wastes and the Price of Recycled Materials in Pennsylvania

Data on the cost of recycling different components of C&D wastes and the sale price of the recycled materials were obtained from different C&D wastes recycling facilities in Pennsylvania and US Environmental Protection Agency (EPA) publication. In some cases where there is limited or no information on the cost of recycling in Pennsylvania, data on the cost of recycling C&D wastes in the neighboring state of New Jersey were also used in estimating the equivalent cost of recycling in Pennsylvania.

The average cost of recycling particular C&D waste components to particular recycled materials or end-use options is estimated as shown in appendix E. According to the estimated values in appendix E, the average unit cost of recycling concrete/ brick/ block/asphalt-combined to mixed aggregates of concrete/brick/block/asphalt is $4.0 per ton. The average unit cost of recycling non-ferrous metals is $0.93 per ton, and the average unit cost of recycling wood to wood chips is $58.97 per ton. Also, the average unit cost of recycling drywall to gypsum agricultural products is $15.00 per ton, and the average unit cost of recycling roofing shingles to asphalt aggregates is $44.50 per ton.

Furthermore, the average sale price of the recycled materials from C&D waste components, collected from recycling facilities in Pennsylvania, is shown in appendix F. The average sale price of recycled aggregates of concrete/brick/block/asphalt in any combination is $6.00 per ton, wood chips is $31.75 per ton and non-ferrous metal is $1.72. Also, the average sale price of gypsum agricultural products (from drywalls recycling) is $20.00. Table 3.8 is the summary of the estimated average tipping fees, Recycling Costs and Sale Price of Recycled Materials from C&D waste components in Pennsylvania in 2010.

Table 3.8: Summary of the Estimated Average Tipping fees, Recycling Cost and Sale Price of Recycled Materials in Pennsylvania in 2010.

RECYCLABLE C&D WASTE COMPONENT, j	END-USE OPTION, rj	ESTIMATED AVERAGE TIPPING FEE PER TON CHARGED BY RECYCLING FACILITIES, u_{rj}	ESTIMATED AVERAGE UNIT COST OF PURCHASING RECYCLABLE C&D WASTE COMPONENT PER TON FOR RECYCLING, e_{rj}	ESTIMATED AVERAGE UNIT COST TO RECYCLE PER TON, C_{rj}	ESTIMATED AVERAGE SALE PRICE PER TON OF RECYCLED MATERIAL, p_{rj}
ASPHALT	**Asphalt Aggregates**	**$ 2.00**	**0.00**	**$ 5.62**	**$ 6.00**
CONCRETE	**Concrete Aggregates**	**$ 2.00**	**0.00**	**$ 5.08**	**$ 6.00**
BRICK/ BLOCK	**Brick/Block Aggregates**	**$ 2.00**	**0.00**	**$ 5.49**	**$ 6.00**
Concrete/ Brick/ Block /Asphalt - Combined	**Mixed Aggregates**	**$ 2.00**	**0.00**	**$ 4.00**	**$ 6.00**
Metals *	**Metals ***	**0.00**	**0.00**	**$ 0.93**	**$ 1.72**
Wood	**Wood Chips**	**$ 31.00**	**0.00**	**$ 58.97**	**$ 31.75**
Drywall	**Gypsum Agric. Products**	**$ 25.00**	**0.00**	**$ 15.00**	**$ 20.00**
Roofing Shingles	**Asphalt Aggregates**	**$ 47.00**	**0.00**	**$ 44.50**	**$ 6.00**

* Only non-ferrous metals are considered since steel recycling has already been a highly profitable business with many recycling facilities and great market for the recycled steels for a long time.

3.3 Development of a Mathematical Model for Effective Recycle Planning for Construction and Demolition Wastes

The mathematical model that is used in this study, effective recycle planning for C&D wastes, is a simple linear integer program that estimates the total cost of recycling C&D wastes recyclable components as the sum of the individual cost of recycling each component to the available market end-use options, and then estimate the total monetary proceed from selling the recycled material end-use options as the sum of the individual proceed from each end-use option of the recycled component; thereby giving the monetary profit as the result of the mathematical program. Thus, enabling stakeholders in construction business to identify C&D waste components that their recycling would yield higher profit or return, and those that their recycling would yield less or no profit. The objective is to minimize cost of recycling C&D wastes, maximize revenue generated from the recycled materials and therefore maximize profit.

The estimated total cost of C&D waste recycling minus the total monetary proceed =

$$\sum_{j=1}^{m} \sum_{srj=1}^{n} \sum_{rj=1}^{l} \{[c_{rj} + 2f_{rj} + e_{rj} + (d_{srj} \times c_j) + (W_{rj} \times b_{rj})] - [(1-W_{rj})p_{rj} + u_{rj}]\} \times K_{rj} \times a_j \leq 0 \quad \textbf{(3.1).}$$

Let $c_{rj} + 2f_{rj} + e_{rj} + (d_{srj} \times c_j) + (W_{rj} \times b_{rj}) = \mathbf{E_{rj}}$ .... **(3.2).**

And let $(1-W_{rj})\, p_{rj} + u_{rj} = \mathbf{R_{rj}}$ .... **(3.3).**

Therefore, equation 3.1 can be simplified into equation 3.4 with the main objective of making profit as follows:

The profit from recycling C&D waste =

$$\sum_{j=1}^{m} \sum_{srj=1}^{n} \sum_{rj=1}^{l} (\mathbf{R_{rj}} - \mathbf{E_{rj}}) \times K_{rj} \times a_j \geq 0 \qquad \textbf{(3.4).}$$

Where $\mathbf{E_{rj}}$ = the entire expenditure or cost of recycling one unit of a particular C&D waste component to a particular end-use option.

$\mathbf{R_{rj}}$ = represents the revenue or proceed from one unit of that particular end-use option.

j = the recyclable component of the C&D waste.

m = the total number of recyclable components of the C&D waste.

srj = the particular area or site (s) where the recyclable component j is generated and transported for recycling into an end-use option (rj).

n = the total number of areas or sites (s) where the recyclable component (j) is generated and transported for recycling into an end-use option (rj).

rj = the available end-use option which the recyclable component (j) can be recycled into.

l = the total number of the available end-use option (rj) which the recyclable component (j) can be recycled into.

C_{rj} = the unit cost of processing the recyclable component (j) to an end-use option (rj).

f_{rj} = the unit cost of loading or unloading the recyclable component (j) transported for recycling into the end-use option (rj).

e_{rj} = is the unit cost of purchasing metal scraps or any other recyclable component (j) for recycling.

d_{srj} = is the distance between the area or site (s) where the recyclable component (j) is generated and the recycling facility for end-use option (rj).

c_j = the unit cost of transporting the recyclable component (j) through a unit distance.

W_{rj} = the ratio or percentage, in decimal number, of the recyclable component j that comes out as by-product after recycling into an end-use option (rj).

b_{rj} = the unit cost of disposing or handling the by-product after recycling the component (j) into an end-use option (rj).

p_{rj} = the unit price of the end-use option (rj) from the recyclable component (j).

u_{rj} = the unit price charged for disposing recyclable component (j) for recycling into end-use option (rj).

a_j = the total quantity of the recyclable component (j) generated in the geographical area or region within a particular period of time.

K_{rj} = the ratio or percentage, in decimal number, of the total quantity (a_j) of the recyclable component (j) generated in the geographical area or region that would be recycled into the end-use option (rj).

Equations 3.1, 3.2, 3.3 and 3.4 can be simplified into equations 3.5, 3.6, 3.7 and 3.8 respectively below, to maximize profit based on the following assumptions:

1. Assuming that the efficiency of the recycling facilities are improved such that the quantity of the by-product from recycling is negligible as compared to the quantity of the recyclable component processed into that particular end-use option, and also assuming that the by-product can be utilized at no cost to the operators of the recycling facilities. Therefore, $W_{rj} = 0$ and $brj = 0$ respectively.

2. Assuming that the loading, transportation and unloading of recyclable C&D waste components is handled separately by other profit-making establishments at no cost to the operators of the C&D recycling facilities. Therefore, $c_j = 0$ and $dsrj = 0$.

3. It is also assumed that all the recyclable C&D waste components collected by the C&D waste transportation managers or establishments would be disposed at the designated

C&D waste recycling facilities; and all the recyclable components would be processed to the desired end-use options with a negligible portion as by-product.

4. Finally, it is assumed that all the end-use options would be purchased after recycling by major dealers; such that the operators of the facilities would not incur any cost of storage for the recycled materials.

From the aforementioned assumptions, equation 3.1, 3.2, 3.3, and 3.4 is simplified into equation 3.5, 3.6, 3.7 and 3.8 respectively to maximize profit from recycling as follows:

The estimated total cost of C&D waste recycling minus the total monetary proceed =

$$\sum_{j=1}^{m} \sum_{srj=1}^{n} \sum_{rj=1}^{l} [(c_{rj} + e_{rj}) - (p_{rj} + u_{rj})] \times K_{rj} \times a_j \leq 0 \quad \textbf{(3.5).}$$

Then, let $c_{rj} + e_{rj} = \mathbf{E_{rj}}$ .... **(3.6).**

And let $p_{rj} + u_{rj} = \mathbf{R_{rj}}$ .... **(3.7).**

Therefore, the maximum profit from recycling C&D waste =

$$\sum_{j=1}^{m} \sum_{srj=1}^{n} \sum_{rj=1}^{l} (\mathbf{R_{rj} - E_{rj}}) \times K_{rj} \times a_j \geq 0 \quad \textbf{(3.8).}$$

Based on equation 3.6, 3.7 and 3.8, the estimated unit profit from recycling one unit quantity of a particular C&D waste component to a particular end-use option =

$$\mathbf{R_{rj} - E_{rj}} \geq 0 \quad \textbf{(3.9).}$$

Finally, equation 3.8 is further simplified into equation 3.10; by considering the recycling of each component separately and dealing only with the quantity of that C&D waste component from one area or site. As such, the area or site where the C&D waste component is generated is considered as a separate geographical area or region.

Hence, the maximum profit for recycling a particular component of C&D wastes from a particular geographical region or area = $\sum_{rj=1}^{I} (\mathbf{R}_{rj} - \mathbf{E}_{rj}) \times K_{rj} \times a_j \geq 0$.... .... **(3.10).**

The simplified linear equation, shown in equation 3.10, is used in this thesis as the Mathematical Model for selecting C&D waste components for recycling in a particular area or region.

The estimated average revenue (per ton), the estimated average expenditure (per ton) and the estimated average unit profit (per ton) from recycling C&D wastes in Pennsylvania are calculated based on equations 3.6, 3.7 and 3.9 respectively. Also, equation 3.10 is used in estimating the maximum profit for recycling a particular component of C&D wastes in Pennsylvania. Table 3.9 summarizes the estimated average revenue (per ton), the estimated average expenditure (per ton) and the estimated average unit profit (per ton) from recycling C&D wastes in Pennsylvania in 2010.

3.4 Logic Structure for Selecting C&D Waste Components for Recycling

As a decision making tool, a logic structure was designed in this study to help stakeholders in construction business in selecting C&D waste components for recycling. The logic structure, combined with the mathematical equations developed in this thesis, enables stakeholders in construction business to identify C&D components that their recycling would yield good profits and those that their recycling would yield less or no profit in their geographical region or area.

Hence, private companies or individuals can invest and participate in the recycling of C&D waste components that yield good profits in their region or area. Then the Government can sponsor or provide incentives for the recycling of C&D waste components that yield no or less profit in order to reduce environmental pollution, conserve natural resources and generate jobs in their geographical area or region. Figure 3.2 shows the logic structure for selecting C&D waste components for recycling.

Table 3.9: Estimated Unit Profit for Recycling a Particular Component of C&D Waste to a Particular End-use Option in Pennsylvania in 2010.

RECYCLABLE C&D COMPONENT, j	END-USE OPTION, rj	ESTIMATED AVERAGE REVENUE PER TON FROM RECYCLING, Rrj	ESTIMATED AVERAGE EXPENDITURE PER TON FOR RECYCLING, Erj	ESTIMATED AVERAGE UNIT PROFIT PER TON FROM RECYCLING, Rrj – Erj
Asphalt	Asphalt Aggregates	$ 8.00	$ 5.62	$ 2.38
Concrete	Concrete Aggregates	$ 8.00	$ 5.08	$ 2.92
Brick/ Block	Brick/Block Aggregates	$ 8.00	$ 5.49	$ 2.51
Concrete/ Brick/ Block /Asphalt - Combined	Mixed Aggregates	$ 8.00	$ 4.00	$ 4.00
Metals *	Metals *	$ 1.72	$ 0.93	$ 0.79
Wood	Wood Chips	$ 62.75	$ 58.97	$ 3.78
Drywall	Gypsum Agric. Products	$ 45.00	$ 15.00	$ 30.00
Roofing Shingles	Asphalt Aggregates	$ 53.00	$ 44.50	$ 8.50

* Only non-ferrous metals are considered since steel recycling has already been a highly profitable business with many recycling facilities and great market for the recycled steels for a long time.

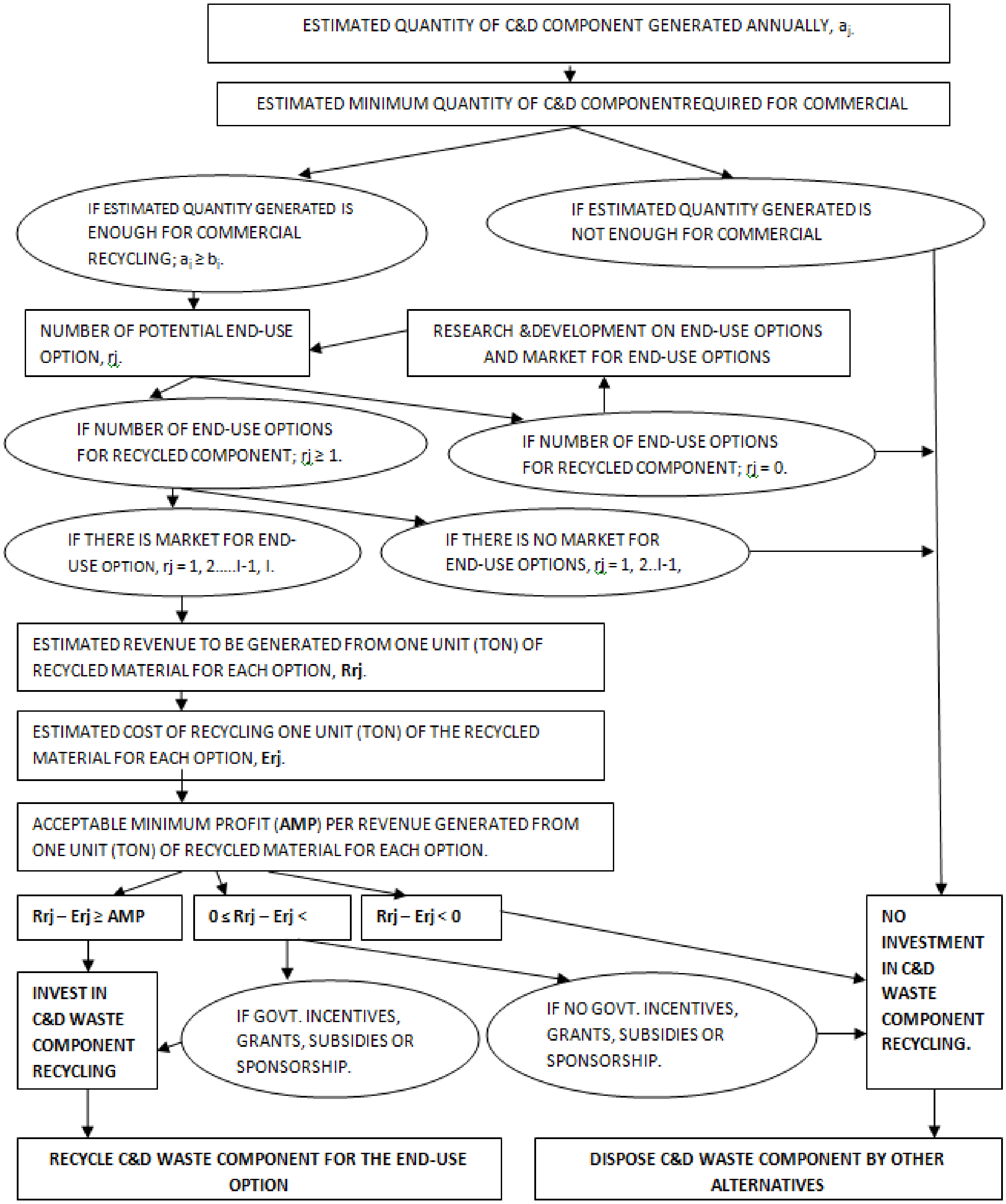


Figure 3.2: Logic Structure for Selecting C&D Waste Components for Recycling.

CHAPTER 4

RESULTS AND ANALYSIS

4.1 Case Study

Based on the estimated quantity of C&D waste components disposed in Pennsylvania in 2009, a case study was conducted to test the model for effective C&D wastes recycling developed in chapter 3. It involves the application of the logic structure for selecting C&D waste components for recycling shown in figure 3.2, and the application of the equations developed in Chapter 3. The objective was to identify the C&D waste components in Pennsylvania that investment in their recycling would yield substantial profit and the components that their recycling would yield less or no profit. The results would lead to decision making on C&D waste components in Pennsylvania that their recycling requires Government incentives or supports and the components that their recycling does not require Government incentives or supports. The estimated quantity of C&D waste components disposed in Pennsylvania in 2009, considered in this case study, is shown in appendix C.

The estimated average unit cost of recycling a particular C&D waste component to a particular end-use option, the estimated average tipping fee charged at recycling facilities per ton of C&D waste component disposed, and the estimated average sale price per ton of the recycled materials in Pennsylvania in 2010, as summarized in table 3.8, is considered in the case study. Also, the estimated unit profit per ton from recycling a particular C&D waste component to a particular end-use option or recycled material in Pennsylvania in 2010, as shown in table 3.9, is applied in this case study. The potential maximum profits from recycling the estimated annual quantity (1,070,165.2 tons) of C&D waste components disposed in entire Pennsylvania in 2009 to some end-use options or recycled materials is calculated using equation 3.10 developed in chapter 3. In addition, the potential maximum profits from recycling the C&D waste components disposed in the top five counties with higher quantity of C&D waste disposal in Pennsylvania in 2009 is calculated separately for each of the counties, using the same equation 3.10 developed in chapter 3.

The five counties that are considered separately are: Allegheny County with 16.9% (180,863 tons) of the total annual quantity (1,070,165.2 tons) disposed in Pennsylvania in 2009, Montgomery County with 7.9% (85,006 tons) of the total annual quantity (1,070,165.2 tons) disposed in Pennsylvania in 2009, Chester County with 7.7% (82,556.4 tons) of the total annual quantity (1,070,165.2 tons) disposed in Pennsylvania in 2009, Lancaster County with 6.3% (66,960.8 tons) of the total annual quantity (1,070,165.2 tons) disposed in Pennsylvania in 2009, and Philadelphia County with 5.3% (56,577 tons) of the total annual quantity (1,070,165.2 tons) disposed in Pennsylvania in 2009. The quantities and percentages of C&D wastes disposed at each county in Pennsylvania in 2009 are shown in appendix C.

As previously stated, it is worth noting that Pennsylvania Department of Environmental Protection (PADEP) does not keep a comprehensive record of the quantities of C&D

wastes disposed at recycling facilities or energy recovery facilities; it mostly records the quantities of C&D wastes disposed at landfills. As such, the quantities of C&D wastes considered above are the quantities disposed mostly at landfills in 2009. Some counties that generated higher quantity of C&D wastes may have disposed a percentage lower than the total quantity generated, if there is a lot of recycling activities going on in the county. For instance, the 5.3% (56,577 tons) disposal in Philadelphia in 2009 may have been much lower than the actual C&D wastes quantity generated in Philadelphia that year. This is based on the assumption that many of the C&D wastes generated may have been recycled, since there is a lot of C&D wastes recycling activities in Philadelphia due to the presence of many C&D recycling companies in the county.

Due to insufficient records or data on the composition or fraction of C&D waste components in Pennsylvania, the estimated C&D waste component fraction in Lancaster County, published by Lancaster County Solid Waste Management Authority (LCSWMA), is adopted for entire Pennsylvania in this case study. Furthermore, the same estimated C&D waste component fraction in Lancaster County is applied to the other top four counties with higher quantity of C&D wastes disposal in Pennsylvania in 2009. Table 3.1 shows the estimated C&D waste component in Lancaster published by Lancaster County Solid Waste Management Authority (LCSWMA).

According to table 3.1, Wood has the highest fraction of 25.6% of the total weight; followed by roofing shingles with 18.0%; concrete/brick/block/dirt/asphalt combined has 17.8%, drywall/plaster has 13.2%, all metals combined has 2.6%, and non-ferrous metals (aluminum in particular) has 0.2% . The fractions (in percentage) are used in estimating the quantity of individual C&D component disposed in Pennsylvania in general, and the quantity of each C&D waste component disposed in Allegheny County, Montgomery County, Chester County, Lancaster and Philadelphia County in particular in 2009. Corrugated containers, with 1.6% of the total weight, and other materials (fiberglass, plastics, porcelain, carpet, linoleum, unspecified), with 20.9% of the total weight, are not considered in this case study. Similarly, only non-ferrous metals are considered in this case study; since steel recycling has already been a highly profitable business with many recycling facilities and a great market for the recycled steels for a long time.

4.1.1 Results and Analysis

Following the application of equation 3.10 and the logic structure for selecting C&D waste components for recycling shown in figure 3.2, the estimated maximum profit for recycling particular C&D components disposed in Pennsylvania in 2009 to particular end-use option is as shown in table 4.1 and figure 4.1. The maximum profit for recycling concrete/brick/block/asphalt-combined to mixed aggregates of concrete/brick/block/asphalt is $761,957.60. Recycling non-ferrous metals would yield $1,690.84. Then, recycling wood to wood chips yields $1,035,577.49. The maximum profit for recycling drywall to gypsum agricultural products is $4,237,854.00, and the maximum profit for recycling roofing shingles disposed in Pennsylvania in 2009 to asphalt aggregates is $1,637,352.45.

Table 4.1: Estimated Maximum Profit for Recycling a Particular Component of C&D Waste to a Particular End-use Option in Pennsylvania Based on the Estimated Annual Quantity of C&D Wastes Disposed in 2009.

RECYCLABLE C&D COMPONENT, j	THE TOTAL QUANTITY OF THE RECYCLABLE C&D COMPONENT IN TONS, aj	END-USE OPTION, rj	MARKET FOR THE END-USE OPTION	PERCENTAGE OF THE TOTAL QUANTITY OF COMPONENT THAT IS RECYCLED, Krj	ESTIMATED AVERAGE REVENUE PER TON FROM RECYCLING, Rrj	ESTIMATED AVERAGE EXPENDITURE PER TON FOR RECYCLING, Erj	ESTIMATED AVERAGE UNIT PROFIT PER TON FROM RECYCLING, Rrj – Erj	ESTIMATED MAXIMUM PROFIT FOR RECYCLING A PARTICULAR COMPONENT
Concrete/ Brick/ Block /Asphalt - Combined	190489.4	Mixed Aggregates (rj=1)	YES	100%	$ 8.00	$ 4.00	$ 4.00	$ 761,957.60
Metals *	2140.3	Metals * (rj=1)	YES	100%	$ 1.72	$ 0.93	$ 0.79	$ 1,690.84
Wood	273962.3	Wood Chips (rj=1)	YES	100%	$ 62.75	$ 58.97	$ 3.78	$1,035,577.49
Drywall	141261.8	Gypsum Agric. Products (rj=1)	YES	100%	$ 45.00	$ 15.00	$ 30.00	$4,237,854.00
Roofing Shingles	192629.7	Asphalt Aggregates (rj=1)	YES	100%	$ 53.00	$ 44.50	$ 8.50	$1,637,352.45

* Only non-ferrous metals are considered since steel recycling has already been a highly profitable business with many recycling facilities and great market for the recycled steels for a long time.

	Mixed Aggregate (rj=1)	Metals * (rj=1)	Wood Chips (rj=1)	Gypsum Agric. Products (rj=1)	Asphalt Aggregate (rj=1)
	190489.4	2140.3	273962.3	141261.8	192629.7
	Concrete/ Brick/ Block /Asphalt - Combined	Metals *	Wood	Drywall	Roofing Shingles
ESTIMATED MAXIMUM PROFIT FOR RECYCLING A PARTICULAR COMPONENT	$761,957.60	$1,690.84	$1,035,577.49	$4,237,854.00	$1,637,352.45
ESTIMATED AVERAGE UNIT PROFIT PER TON FROM RECYCLING, Rrj – Erj	$4.00	$0.79	$3.78	$30.00	$8.50

Figure 4.1: Estimated Maximum Profit for Recycling a Particular Component of C&D Wastes Based on the Quantity Disposed 2009 in PA.

According to table 4.1 or figure 4.1, the recycling of drywall to gypsum agricultural products yields good annual profit of $4,237,854.00 and the component is available in commercial quantities. Also, the recycling of roofing shingles to asphalt aggregates, and the recycling of wood to wood chips yield annual profits of $1,637,352.45 and $1,035,577.49 respectively and the components are available in commercial quantities. As such, the recycling of drywalls, roofing shingles and wood in Pennsylvania is profitable enough for individuals or private companies to invest; even without financial support or incentives from government.

On the other hand, according to table 4.1 or figure 4.1, though concrete/brick/block /asphalt-combined are available in commercial quantity for recycling, their recycling does not yield enough annual profit. The annual maximum profit ($761,957.60) for recycling concrete/brick/block/asphalt-combined, based on the quantity disposed in Pennsylvania in 2009, is less than $1,000,000 and may not be profitable enough for individuals or private companies to invest without some financial incentives from the government. Hence, government supports or incentives are still required in other to encourage individual or private investors to invest in the recycling of concrete/brick/block/asphalt-combined in Pennsylvania.

Also, from table 4.1 or figure 4.1, the annual quantity of recyclable non-ferrous metals from C&D wastes disposed in Pennsylvania in 2009 is so small and the annual maximum profit ($1,690.84) for recycling this component is too small for commercial investment. Based on these results, it would not be profitable for individuals or private companies to make new investments in the recycling of non-ferrous metals from C&D wastes disposed in Pennsylvania. Instead, government should encourage the transportation of this component to already existing companies that are dealing with metal recycling in the state or neighboring states. Government can provide incentive such as tax break to companies that separate and transport non-ferrous metals to already existing metal recycling companies in the state or neighboring states.

Furthermore, the potential maximum profits for recycling the C&D waste components disposed in the top five counties with higher quantity of C&D waste disposal in Pennsylvania in 2009 is calculated separately to help potential investors in making decisions on where to establish or locate a new C&D waste recycling facilities. The counties, starting from the one with the highest quantity of C&D waste disposal in 2009, are Allegheny, Montgomery, Chester, Lancaster and Philadelphia.

The potential maximum profits for recycling particular components of C&D wastes to particular end-use options in Allegheny, Montgomery, Chester, Lancaster and Philadelphia counties are shown in table 4.2, table 4.3, table 4.4, table 4.5 and table 4.6 respectively. Also, Figure 4.2, figure 4.3, figure 4.4, figure 4.5 and figure 4.6 are the graphical representations of the maximum profits for recycling in Allegheny, Montgomery, Chester, Lancaster and Philadelphia respectively; based on the quantity of C&D disposed in 2009. According to the tables and figures, the maximum profit for recycling each component considered in the case study in each of these five counties depends on the percentage of the total quantity of that components (disposed in entire Pennsylvania in 2009) that is disposed in that particular county alone.

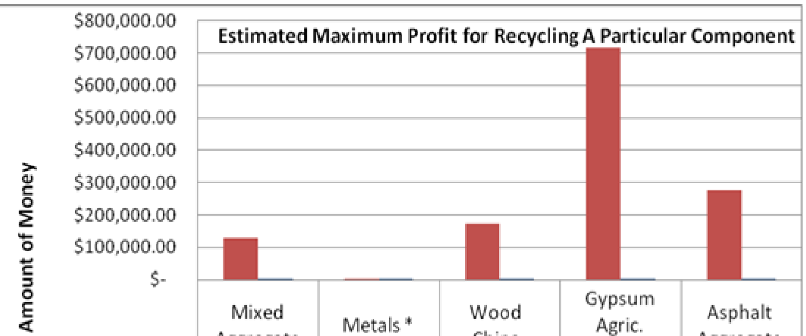
Based on the annual quantity of C&D wastes disposed in 2009 in Pennsylvania, the maximum profits for recycling concrete/brick/block/asphalt-combined to mixed aggregates of concrete/brick/ block/asphalt in Allegheny, Montgomery, Chester, Lancaster and Philadelphia counties are $128,774.40, $60,524.40, $58,780.00, $47,676.00, and $40,282.80 respectively. Also, the maximum profits for recycling non-ferrous metals (based on the annual quantity of C&D wastes disposed in 2009) in Allegheny, Montgomery, Chester, Lancaster and Philadelphia counties are $285.74, $134.30, $130.43, $105.78 and $89.43 respectively. Then, the maximum profits for recycling wood to wood chips (based on the annual quantity of C&D wastes disposed in 2009) in Allegheny, Montgomery, Chester, Lancaster and Philadelphia counties are $175,017.40, $82,258.47, $79,888.03, $64,796.76 and $54,748.39 respectively.

In addition, the maximum profits for recycling drywall to gypsum agricultural products (based on the annual quantity of C&D wastes disposed in 2009) in Allegheny, Montgomery, Chester, Lancaster and Philadelphia counties are $716,217.00, $336,624.00, $326,922.00, $265,164.00 and $224,046.00 respectively. Finally, the maximum profits for recycling roofing shingles to asphalt aggregates (based on the annual quantity of C&D wastes disposed in 2009) in Allegheny, Montgomery, Chester, Lancaster and Philadelphia counties are $267,720.05, $130,059.35, $126,311.70, $102,449.65 and $86,563.15 respectively.

Table 4.2: Estimated Maximum Annual Profit for Recycling a Particular Component of C&D Waste to a Particular End-use Option in Allegheny County in PA Based on the Estimated Annual Quantity of C&D Wastes Disposed in 2009.

RECYCLABLE C&D COMPONENT, j	THE TOTAL QUANTITY OF THE RECYCLABLE C&D COMPONENT IN TONS, aj	END-USE OPTION, rj	MARKET FOR THE END-USE OPTION	PERCENTAGE OF THE TOTAL QUANTITY OF COMPONENT THAT IS RECYCLED, Krj	ESTIMATED AVERAGE REVENUE PER TON FROM RECYCLING, Rrj	ESTIMATED AVERAGE EXPENDITURE PER TON FOR RECYCLING, Erj	ESTIMATED AVERAGE UNIT PROFIT PER TON FROM RECYCLING, Rrj – Erj	ESTIMATED MAXIMUM PROFIT FOR RECYCLING A PARTICULAR COMPONENT
Concrete/ Brick/Block/ Asphalt - Combined	32193.6	Mixed Aggregates (rj=1)	YES	100%	$ 8.00	$ 4.00	$ 4.00	$ 128,774.40
Metals *	361.7	Metals * (rj=1)	YES	100%	$ 1.72	$ 0.93	$ 0.79	$ 285.74
Wood	46300.9	Wood Chips (rj=1)	YES	100%	$ 62.75	$ 58.97	$ 3.78	$ 175,017.40
Drywall	23873.9	Gypsum Agric. Products (rj=1)	YES	100%	$ 45.00	$ 15.00	$ 30.00	$ 716,217.00
Roofing Shingles	32555.3	Asphalt Aggregates (rj=1)	YES	100%	$ 53.00	$ 44.50	$ 8.50	$ 276,720.05

* Only non-ferrous metals are considered since steel recycling has already been a highly profitable business with many recycling facilities and great market for the recycled steels for a long time.



	Mixed Aggregate (rj=1) 32193.6 Concrete/ Brick/ Block / Asphalt - Combined	Metals * (rj=1) 361.7 Metals *	Wood Chips (rj=1) 46300.9 Wood	Gypsum Agric. Products (rj=1) 23873.9 Drywall	Asphalt Aggregate (rj=1) 32555.3 Roofing Shingles
ESTIMATED MAXIMUM PROFIT FOR RECYCLING A PARTICULAR COMPONENT	$128,774.40	$285.74	$175,017.40	$716,217.00	$276,720.05
ESTIMATED AVERAGE UNIT PROFIT PER TON FROM RECYCLING, Rrj – Erj	$4.00	$0.79	$3.78	$30.00	$8.50

Figure 4.2: Estimated Maximum Profit for Recycling a Particular Component of C&D Wastes Based on the Quantity Disposed 2009 in Allegheny County in PA.

Table 4.3: Estimated Maximum Annual Profit for Recycling a Particular Component of C&D Waste to a Particular End-use Option in Montgomery County in PA Based on the Estimated Annual Quantity of C&D Wastes Disposed in 2009.

RECYCLABLE C&D COMPONENT, j	THE TOTAL QUANTITY OF THE RECYCLABLE C&D COMPONENT IN TONS, aj	END-USE OPTION, rj	MARKET FOR THE END-USE OPTION	PERCENTAGE OF THE TOTAL QUANTITY OF COMPONENT THAT IS RECYCLED, Krj	ESTIMATED AVERAGE REVENUE PER TON FROM RECYCLING, Rrj	ESTIMATED AVERAGE EXPENDITURE PER TON FOR RECYCLING, Erj	ESTIMATED AVERAGE UNIT PROFIT PER TON FROM RECYCLING, Rrj – Erj	ESTIMATED MAXIMUM PROFIT FOR RECYCLING A PARTICULAR COMPONENT
Concrete/Brick/ Block / Asphalt -Combined	**15131.1**	**Mixed Aggregates (rj=1)**	**YES**	**100%**	**$ 8.00**	**$ 4.00**	**$ 4.00**	**$ 60,524.40**
Metals *	**170**	**Metals * (rj=1)**	**YES**	**100%**	**$ 1.72**	**$ 0.93**	**$ 0.79**	**$ 134.30**
Wood	**21761.5**	**Wood Chips (rj=1)**	**YES**	**100%**	**$ 62.75**	**$ 58.97**	**$ 3.78**	**$ 82,258.47**
Drywall	**11220.8**	**Gypsum Agric. Products (rj=1)**	**YES**	**100%**	**$ 45.00**	**$ 15.00**	**$ 30.00**	**$ 336,624.00**
Roofing Shingles	**15301.1**	**Asphalt Aggregates (rj=1)**	**YES**	**100%**	**$ 53.00**	**$ 44.50**	**$ 8.50**	**$ 130,059.35**

* Only non-ferrous metals are considered since steel recycling has already been a highly profitable business with many recycling facilities and great market for the recycled steels for a long time.

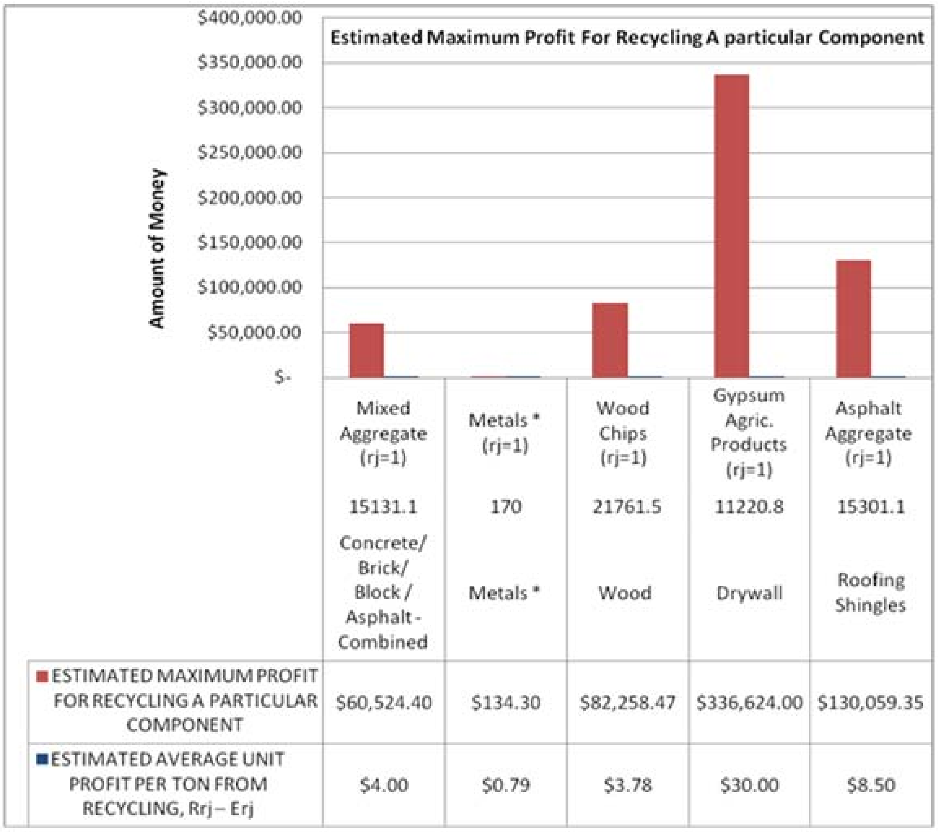
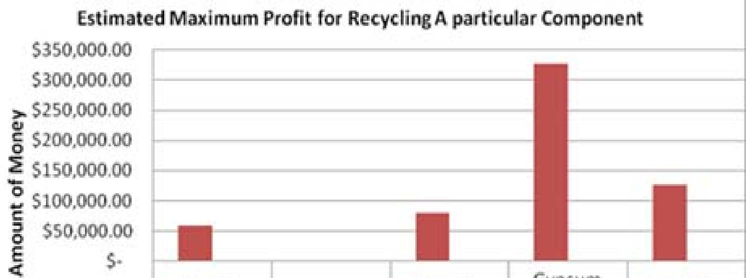


Figure 4.3: Estimated Maximum Profit for Recycling a Particular Component of C&D Wastes Based on the Quantity Disposed 2009 in Montgomery County in PA.

Table 4.4: Estimated Maximum Annual Profit for Recycling a Particular Component of C&D Waste to a Particular End-use Option in Chester County in PA Based on the Estimated Annual Quantity of C&D Wastes Disposed in 2009.

RECYCLABLE C&D COMPONENT, j	THE TOTAL QUANTITY OF THE RECYCLABLE C&D COMPONENT IN TONS, aj	END-USE OPTION, rj	MARKET FOR THE END-USE OPTION	PERCENTAGE OF THE TOTAL QUANTITY OF COMPONENT THAT IS RECYCLED, Krj	ESTIMATED AVERAGE REVENUE PER TON FROM RECYCLING, Rrj	ESTIMATED AVERAGE EXPENDITURE PER TON FOR RECYCLING, Erj	ESTIMATED AVERAGE UNIT PROFIT PER TON FROM RECYCLING, Rrj – Erj	ESTIMATED MAXIMUM PROFIT FOR RECYCLING A PARTICULAR COMPONENT
Concrete/ Brick/Block /Asphalt - Combined	14695	Mixed Aggregates (rj=1)	YES	100%	$ 8.00	$ 4.00	$ 4.00	$ 58,780.00
Metals *	165.1	Metals * (rj=1)	YES	100%	$ 1.72	$ 0.93	$ 0.79	$ 130.43
Wood	21134.4	Wood Chips (rj=1)	YES	100%	$ 62.75	$ 58.97	$ 3.78	$ 79,888.03
Drywall	10897.4	Gypsum Agric. Products (rj=1)	YES	100%	$ 45.00	$ 15.00	$ 30.00	$ 326,922.00
Roofing Shingles	14860.2	Asphalt Aggregates (rj=1)	YES	100%	$ 53.00	$ 44.50	$ 8.50	$ 126,311.70

* Only non-ferrous metals are considered since steel recycling has already been a highly profitable business with many recycling facilities and great market for the recycled steels for a long time.



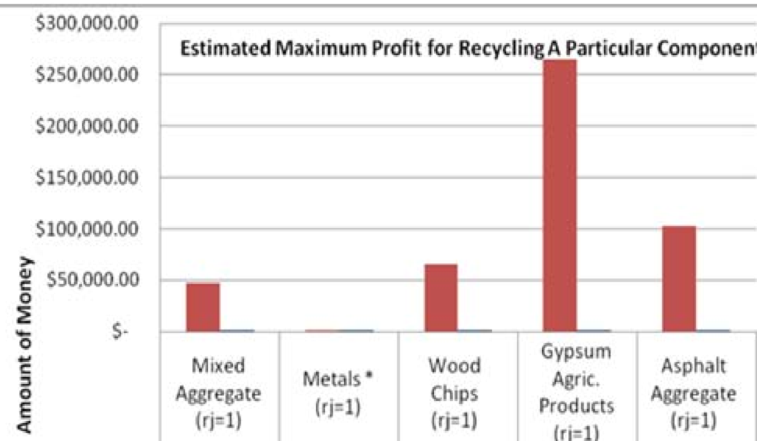
	Mixed Aggregate (rj=1) 14695 Concrete/ Brick/ Block /Asphalt-Combined	Metals * (rj=1) 165.1 Metals *	Wood Chips (rj=1) 21134.4 Wood	Gypsum Agric. Products (rj=1) 10897.4 Drywall	Asphalt Aggregate (rj=1) 14860.2 Roofing Shingles
ESTIMATED MAXIMUM PROFIT FOR RECYCLING A PARTICULAR COMPONENT	$58,780.00	$130.43	$79,888.03	$326,922.00	$126,311.70
ESTIMATED AVERAGE UNIT PROFIT PER TON FROM RECYCLING, Rrj – Erj	$4.00	$0.79	$3.78	$30.00	$8.50

Figure 4.4: Estimated Maximum Profit for Recycling a Particular Component of C&D Wastes Based on the Quantity Disposed 2009 in Chester County in PA.

Table 4.5: Estimated Maximum Annual Profit for Recycling a Particular Component of C&D Waste to a Particular End-use Option in Lancaster County in PA Based on the Estimated Annual Quantity of C&D Wastes Disposed in 2009.

RECYCLABLE C&D COMPONENT, j	THE TOTAL QUANTITY OF THE RECYCLABLE C&D COMPONENT IN TONS, aj	END-USE OPTION, rj	MARKET FOR THE END-USE OPTION	PERCENTAGE OF THE TOTAL QUANTITY OF COMPONENT THAT IS RECYCLED, Krj	ESTIMATED AVERAGE REVENUE PER TON FROM RECYCLING, Rrj	ESTIMATED AVERAGE EXPENDITURE PER TON FOR RECYCLING, Erj	ESTIMATED AVERAGE UNIT PROFIT PER TON FROM RECYCLING, Rrj – Erj	ESTIMATED MAXIMUM PROFIT FOR RECYCLING A PARTICULAR COMPONENT
Concrete /Brick /Block/ Asphalt -Combined	**11919**	**Mixed Aggregates (rj=1)**	**YES**	**100%**	**$ 8.00**	**$ 4.00**	**$ 4.00**	**$ 47,676.00**
Metals *	**133.9**	**Metals * (rj=1)**	**YES**	**100%**	**$ 1.72**	**$ 0.93**	**$ 0.79**	**$ 105.78**
Wood	**17142**	**Wood Chips (rj=1)**	**YES**	**100%**	**$ 62.75**	**$ 58.97**	**$ 3.78**	**$ 64,796.76**
Drywall	**8838.8**	**Gypsum Agric. Products (rj=1)**	**YES**	**100%**	**$ 45.00**	**$ 15.00**	**$ 30.00**	**$ 265,164.00**
Roofing Shingles	**12052.9**	**Asphalt Aggregates (rj=1)**	**YES**	**100%**	**$ 53.00**	**$ 44.50**	**$ 8.50**	**$ 102,449.65**

* Only non-ferrous metals are considered since steel recycling has already been a highly profitable business with many recycling facilities and great market for the recycled steels for a long time.



	Mixed Aggregate (rj=1)	Metals * (rj=1)	Wood Chips (rj=1)	Gypsum Agric. Products (rj=1)	Asphalt Aggregate (rj=1)
	11919	133.9	17142	8838.8	12052.9
	Concrete / Brick / Block/ Asphalt - Combined	Metals *	Wood	Drywall	Roofing Shingles
ESTIMATED MAXIMUM PROFIT FOR RECYCLING A PARTICULAR COMPONENT	$47,676.00	$105.78	$64,796.76	$265,164.00	$102,449.65
ESTIMATED AVERAGE UNIT PROFIT PER TON FROM RECYCLING, Rrj – Erj	$4.00	$0.79	$3.78	$30.00	$8.50

Figure 4.5: Estimated Maximum Profit for Recycling a Particular Component of C&D Wastes Based on the Quantity Disposed 2009 in Lancaster County in PA.

Table 4.6: Estimated Maximum Annual Profit for Recycling a Particular Component of C&D Waste to a Particular End-use Option in Philadelphia County in PA Based on the Estimated Annual Quantity of C&D Wastes Disposed in 2009.

RECYCLABLE C&D COMPONENT, j	THE TOTAL QUANTITY OF THE RECYCLABLE C&D COMPONENT IN TONS, aj	END-USE OPTION, rj	MARKET FOR THE END-USE OPTION	PERCENTAGE OF THE TOTAL QUANTITY OF COMPONENT THAT IS RECYCLED, Krj	ESTIMATED AVERAGE REVENUE PER TON FROM RECYCLING, Rrj	ESTIMATED AVERAGE EXPENDITURE PER TON FOR RECYCLING, Erj	ESTIMATED AVERAGE UNIT PROFIT PER TON FROM RECYCLING, Rrj – Erj	ESTIMATED MAXIMUM PROFIT FOR RECYCLING A PARTICULAR COMPONENT
Concrete/ Brick /Block/ Asphalt - Combined	10070.7	Mixed Aggregates (rj=1)	YES	100%	$ 8.00	$ 4.00	$ 4.00	$ 40,282.80
Metals *	113.2	Metals * (rj=1)	YES	100%	$ 1.72	$ 0.93	$ 0.79	$ 89.43
Wood	14483.7	Wood Chips (rj=1)	YES	100%	$ 62.75	$ 58.97	$ 3.78	$ 54,748.39
Drywall	7468.2	Gypsum Agric. Products (rj=1)	YES	100%	$ 45.00	$ 15.00	$ 30.00	$ 224,046.00
Roofing Shingles	10183.9	Asphalt Aggregates (rj=1)	YES	100%	$ 53.00	$ 44.50	$ 8.50	$ 86,563.15

* Only non-ferrous metals are considered since steel recycling has already been a highly profitable business with many recycling facilities and great market for the recycled steels for a long time.

	Mixed Aggregate (rj=1) 10070.7 Concrete/ Brick /Block/ Asphalt-Combined	Metals * (rj=1) 113.2 Metals *	Wood Chips (rj=1) 14483.7 Wood	Gypsum Agric. Products (rj=1) 7468.2 Drywall	Asphalt Aggregate (rj=1) 10183.9 Roofing Shingles
ESTIMATED MAXIMUM PROFIT FOR RECYCLING A PARTICULAR COMPONENT	$40,282.80	$89.43	$54,748.39	$224,046.00	$86,563.15
ESTIMATED AVERAGE UNIT PROFIT PER TON FROM RECYCLING, Rrj – Erj	$4.00	$0.79	$3.78	$30.00	$8.50

Figure 4.6: Estimated Maximum Profit for Recycling a Particular Component of C&D Wastes Based on the Quantity Disposed 2009 in Philadelphia County in PA.

It could be observed from the results that the maximum profit for recycling each component considered in this case study in each of these five counties depends on the percentage of the total quantity of that components (disposed in entire Pennsylvania in 2009) that is disposed in that particular county alone. The maximum profit for each component considered decreases from Allegheny County with 16.9% of the total quantity of C&D wastes disposed in 2009 in Pennsylvania, Montgomery with 7.9%, Chester with 7.7%, Lancaster with 6.3%, to Philadelphia County with 5.3% of the total quantity of C&D wastes disposed in 2009 in Pennsylvania.

Hence, when deciding on which county or counties to site new C&D waste recycling facilities, the potential investors need to consider the county or counties with high C&D wastes disposal rate in order to minimize the cost of transporting the C&D waste components to the recycling facilities. Lower cost of transporting C&D waste components to recycling facility, among other factors, would encourage stakeholders in building or construction industry to recycle their C&D wastes. Also, high C&D waste disposal in a particular county may also indicate that there are insufficient recycling facilities or no recycling facility in that county and probably its neighboring counties. Thus, locating C&D waste recycling facilities in county or counties with high C&D waste disposal rate would help the potential investor to avoid unnecessary competition from existing C&D waste recycling facility or facilities.

As such, it would be more profitable, even without government incentives or supports, for stakeholders in building or construction industry in Pennsylvania to invest in the recycling of drywall to gypsum agricultural products, the recycling of roofing shingles to asphalt aggregates, and the recycling of wood to wood chips; by considering Allegheny county as the first, Montgomery county as the second, Chester county as the third, Lancaster county as the fourth and Philadelphia as the fifth best locations for any new C&D wastes recycling facility. On the other hand, locating any new C&D waste recycling facility in other counties with very low C&D waste disposal quantity may not be profitable enough for private or individual investors, except there are government incentives that encourage the transportation of C&D wastes from other counties with lower C&D waste disposal rate to the new recycling facility.

As stated before, investing in the recycling of concrete/brick/block/asphalt-combined to mixed aggregates of concrete/brick/block/asphalt, irrespective of the county that the facility is to be located, would not be profitable enough except there are government incentives that encourage the stakeholder to invest and participate in the recycling of this component of C&D wastes. The incentives can be in form of grant or tax break to all stakeholders in building or construction industry that invest or participate in the recycling of concrete/brick/block/asphalt-combined and those that purchase or use recycled aggregates from concrete/brick/block/asphalt.

Also, as mentioned before, the annual quantity of recyclable non-ferrous metals from C&D wastes disposed in Pennsylvania is too small and the estimated annual maximum profit ($1,690.84) for recycling this component is also too small for commercial investment in its recycling. Thus, irrespective of government incentives or county considered as the location for any new recycling facility, it would not be profitable to make new investments in the recycling of non-ferrous metals from C&D wastes disposed in Pennsylvania.

However, government should encourage the transportation of non-ferrous metals from C&D wastes to already existing facilities that are dealing with metal recycling in the state or neighboring states. Government can provide incentive such as tax break to companies, individuals or stakeholders in building or construction industry that separate and transport non-ferrous metals to already existing metal recycling companies in the state or neighboring states for recycling.

4.2 Summary of Results

- The recycling of drywall to gypsum agricultural products yields the highest estimated average unit profit (per ton) of $30.00. As such, though the quantity of drywall disposed in Pennsylvania in 2009 (141,261.8 tons) is less than that of wood (273,962.3 tons), roofing shingles (192,629.7 tons) and concrete/brick/block /asphalt-combined (190,489.4 tons), its recycling yields the highest annual maximum profit of $4,237,854.00. Therefore, the recycling of drywall to gypsum agricultural products yields good profit and stakeholders in construction industry can invest in it, without requiring government incentives or support.

- Roofing shingles has the second higher rate of C&D waste disposal (192,629.7 tons) in Pennsylvania in 2009. The recycling of roofing shingles to asphalt aggregates yields the second higher estimated average unit profit per ton ($8.50) and second higher annual maximum profit ($1,637,352.45). Hence, the recycling of roofing shingles to asphalt aggregates is profitable enough for individuals or private companies to invest in, without government support or incentives.
- Though wood has the highest rate of C&D wastes disposal (273,962.3 tons) in Pennsylvania in 2009, the recycling of wood to wood chips yields an estimated average unit profit of $3.78 and estimated annual maximum profit of $1,035,577.49; which represent the fourth higher average unit profit and the third higher maximum profits for recycling respectively. Even though the estimated average unit profit is low, the annual maximum profit for recycling wood to wood chips is profitable enough for private investment without government support or incentives.
- concrete/brick/block/asphalt-combined has the third higher rate of C&D wastes disposal (190,489.4 tons) in Pennsylvania in 2009, and the recycling of concrete/brick/block/asphalt-combined to mixed aggregates of concrete/brick/block/asphalt also yields the third higher estimated average unit profit of $4.00. However, the recycling of concrete/brick/block/asphalt-combined to mixed aggregates only yields an estimated annual maximum profit

of $761,957.60; and it would not be profitable enough for individual or private companies to invest in, without government incentives or support.

- The quantity of non-ferrous metals (2,140.3 tons) disposed in Pennsylvania in 2009 is the lowest. Also, the estimated average unit profit ($0.93) and the estimated annual maximum profit ($1,690.84) for recycling non-ferrous metals are the lowest. Hence, even with government support, it would not be profitable to invest in new facility that recycles non-ferrous metals from C&D wastes. As such, government should encourage disposal at existing metal recycling facilities.
- To reduce transportation cost and thus encourage stakeholders in construction industry to participate in C&D waste recycling, Allegheny, Montgomery, Chester, Lancaster and Philadelphia counties are considered as the first, second, third, fourth and fifth best locations, respectively, for any new C&D wastes recycling facility. These counties may be assisted by state or federal government with providing tax breaks and other incentives to encourage C&D wastes recycling.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This thesis emphasized the need for all stakeholders in building or construction industry to invest and participate in the recycling of construction and demolition wastes generated by the industry. The existing landfills have limited capacities and can only handle C&D waste disposal for a limited period of time. Also, there are limited lands or spaces for constructing new landfills to handle potential C&D waste generated in the near future. Hence, investing and participating in C&D waste recycling is of paramount importance, not only to reduce construction cost, but to also prevent environmental pollution and conserve natural resources.

Since previous studies have already shown that it is cost-effective to dispose C&D wastes at recycling facilities than disposing at landfills, a mathematical model is developed in this research to estimate or evaluate the potential profits for recycling particular components of C&D wastes to a particular recycled materials or end-use options. Also, logic structure for selecting C&D waste components for recycling is developed in this research.

Factors such as the unit cost (per ton) of recycling C&D waste components to particular recycled materials, the tipping fee charged for disposing C&D components, the sale price (per ton) of the recycled materials and the total quantity of C&D waste components disposed in a region or area are taken into consideration by the mathematical model. In addition, a case study was conducted in Pennsylvania to test the mathematical model and the test has been successful. Thus, the application of the mathematical model and the logic structure for selecting C&D waste for recycling, developed in this study, will be effective in assisting stakeholders to make decisions on establishing new C&D wastes recycling facilities in their areas.

Based on the mathematical model and logic structure for selecting C&D waste components for recycling, C&D waste components, including drywall, roofing shingles and wood, which their recycling yield good profits and require no government support or incentives are identified. Moreover, C&D waste components, such as concrete/brick/block/asphalt-combined, that their recycling does not yield good profits and require government support are also identified. The result of the case study also shows that the quantity of non-ferrous metals in C&D wastes are very small and their recycling yield insignificant profit.

5.2 Expected Benefits

The expected benefits of developing a mathematical model and logic structure for selecting C&D waste components for recycling include, but not limited to the following: First, to assist individuals or private companies in identifying, investing and participating in the recycling of waste components that their recycling yields good monetary profits.

Secondly, to help the government in identifying C&D waste components that their recycling yields less or no monetary profits, and thus support or participate in their recycling to reduce environmental pollution and conserve natural resources. Finally, to encourage all stakeholders in construction industry to participate in effective recycling of C&D wastes generated in their regions or areas.

5.3 Recommendations for Further Research

Due to limited time required for the completion of this thesis and the fact that many owners of the existing C&D waste recycling companies in Pennsylvania were reluctant to provide data for this research, very limited data are utilized in this thesis. As such, it is recommended that construction industry and the government at all levels work together to develop a broader and more comprehensive database, models and computer programs that would assist stakeholders in construction industry in planning, investing and participating effectively in C&D waste recycling in their regions.

Availability of broader database, comprehensive models or computer programs for effective recycling of C&D waste would encourage participation in C&D wastes recycling, reduce construction cost, prevent environmental pollution and conserve resources. Finally, government, construction contractors and managers should invest in research or studies that identify more cost-effective ways of recycling C&D wastes to more profitable recycled materials or end-use options with higher marketability or demand.

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Miller's Wood Recycling, Industrial Park R.D, Lewistown, PA, 2010.

Winzinger Recycling, Delaware & Allegheny Ave., Philadelphia, PA, (www.winzinger.com), 2010.

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http://www.epa.gov/osw/conserve/rrr/imr/cdm/pubs/roof_br.pdf), 2009B.

http://www.epa.gov/epaoswer/osw/pub-c.htm, 1999.

APPENDIX A

END USER TYPE OF DEMOLITION AND CONSTRUCTION WASTES RECYCLING FACILITIES IN PA

ID	Facility	Commodities		
		Commodity	Group	Comment
2261	**AGRECYCLE, INC.** P.O. BOX 38783 PITTSBURGH PA 15238-8783 **Contact:** CARLA CASTAGNERO **Phone:** 412-767-7645 **Email:** carla@agrecycle.com **URL:** **County:** Allegheny **Facility Type ID:** 5 **Facility Type:** End User	Construction & Demolition Debris	Construction/Demolition Debris	Accepts a very limited amount of clean gypsum wallboard.
		Commodity	Group	Comment
2248	**CONSTRUCTION, DEMOLITION, & RECYCLING, INC.** 1060 INDUSTRIAL BLVD. SOUTHAMPTON PA 18966 **Contact:** **Phone:** 215-322-2372 **Email:** cdrtransferstation@verizon.net **URL:** www.cdrtransferstation.com **County:** Bucks **Facility Type ID:** 5 **Facility Type:** End User	Construction & Demolition Debris	Construction/Demolition Debris	Concrete, cinder blocks, brick, asphalt. Also accept Creosote Railroad Ties.

Source: PADEP 2010. (http://www.ahs2.dep.state.pa.us/recycle_markets/SearchResults.aspx).

APPENDIX A CONTINUES: **END USER TYPE OF DEMOLITION AND CONSTRUCTION WASTES RECYCLING FACILITIES IN PA**				
ID	**Facility**	**Commodities**		
		Commodity	**Group**	**Comment**
2576	**B & R RECYCLING** 6370 BASHORE ROAD MECHANICSBURG PA 17055 **Contact:** WILLIAM FOUST **Phone:** 717-697-3881 **Email:** **URL:** **County:** Cumberland **Facility Type ID:** 5 **Facility Type:** End User	Construction & Demolition Debris	Construction/Demolition Debris	
		Commodity	**Group**	**Comment**
4089	**Armstrong World Industries** 2500 Columbia Ave. Lancaster PA 17603 **Contact:** Keith D. Mullen **Phone:** 877-276-7876 **Email:** kdmullen@armstrong.com **URL:** www.armstrong.com/recycle **County:** Lancaster **Facility Type ID:** 5 **Facility Type:** End User	Construction & Demolition Debris	Construction/Demolition Debris	Recycles Acoustical Ceiling Tile only.

Source: PADEP 2010. (http://www.ahs2.dep.state.pa.us/recycle_markets/SearchResults.aspx).

APPENDIX A CONTINUES: **END USER TYPE OF DEMOLITION AND CONSTRUCTION WASTES RECYCLING FACILITIES IN PA**

ID	Facility	Commodity	Group	Comment
3086	**MILLER'S WOOD RECYCLING** 65 INDUSTRIAL PARK RD. LEWISTOWN PA 17044 **Contact:** GARY MILLER **Phone:** 717-248-9663 **Email:** mwrllc@verizon.net **URL:** **County:** Mifflin **Facility Type ID:** 5 **Facility Type:** End User	Construction & Demolition Debris	Construction/Demolition Debris	
2246	**DELAWARE VALLEY RECYCLING** 3107 SOUTH 61ST ST. PHILADELPHIA PA 19153 **Contact:** **Phone:** 215-724-2244 **Email:** **URL:** www.hkgroup.com **County:** Philadelphia **Facility Type ID:** 5 **Facility Type:** End User	Construction & Demolition Debris	Construction/Demolition Debris	Clean Concrete, Asphalt, Brick And Cinder Block

Source: PADEP 2010. (http://www.ahs2.dep.state.pa.us/recycle_markets/SearchResults.aspx).

APPENDIX A CONTINUES: **END USER TYPE OF DEMOLITION AND CONSTRUCTION WASTES RECYCLING FACILITIES IN PA**				
ID	**Facility**	**Commodities**		
3484	**WINZINGER RECYCLING** DELAWARE & ALLEGHENY AVE. PHILADELPHIA PA 19131 **Contact:** PHIL **Phone:** 215-425-4422 **Email:** info@winzinger.com **URL:**www.winzinger.com **County:** Philadelphia **Facility Type ID:** 5 **Facility Type:** End User	**Commodity** Construction & Demolition Debris	**Group** Construction/Demolition Debris	**Comment** Clean And Separated Concrete, Asphal Brick, Cinder Block.
2247	**CEDAR HOLLOW RECYCLING** 100 PARADISE ST. PHOENIXVILLE PA 19460 **Contact:** BILL HUDOME **Phone:** 610-983-0193 **Email:** **URL:** **County:** Chester **Facility Type ID:** 5 **Facility Type:** End User	**Commodity** Construction & Demolition Debris	**Group** Construction/Demolition Debris	**Comment** Clean Concrete And Asphalt.

Source: PADEP 2010. (http://www.ahs2.dep.state.pa.us/recycle_markets/SearchResults.aspx).

APPENDIX B

C&D WASTES RECYCLING DATA AND THEIR SOURCES

Data on C&D Wastes Recycling Obtained from Winzinger Recycling, Delaware & Allegheny Ave., Philadelphia, PA.

C&D COMPONENT	ESTIMATED AVERAGE TIPPING FEE PER TON CHARGED BY RECYCLING FACILITIES	ESTIMATED AVERAGE COST TO RECYCLE PER TON	ESTIMATED AVERAGE SALE PRICE PER TON OF RECYCLED MATERIAL
ASPHALT DEBRIS	$2.00	$4.00	$6.00
CONCRETE RUBBLE	$2.00	$4.00	$6.00
USED BRICKS/BLOCKS	$2.00	$4.00	$6.00
USED BRICKS/BLOCKS, CONCRETE & ASPHALT IN ANY COMBINATION	$2.00	$4.00	$6.00

Source: Winzinger Recycling, Delaware & Allegheny Ave., Philadelphia, PA, (www.winzinger.com), 2010.

Data on C&D Wastes Recycling Obtained from USA GYPSUM, Texter Mountain Road, Reinholds, PA.

C&D COMPONENT	ESTIMATED AVERAGE TIPPING FEE CHARGED BY RECYCLING FACILITIES PER TON	ESTIMATED AVERAGE COST TO RECYCLE PER TON	ESTIMATED AVERAGE SALE PRICE OF RECYCLED MATERIAL (AGRICULTURAL PRODUCTS) PER TON
DRYWALL/PLASTERS	$25.00	$15.00	$20.00

Source: USA GYPSUM, Texter Mountain Road, Reinholds, PA, (http://www.usagypsum.com), 2010.

APPENDIX B continues

DATA ON C&D WASTES RECYCLING UTILIZED IN THE STUDY AND THEIR SOURCES

Data on C&D Wastes Recycling Obtained from Miller's Wood Recycling, Industrial Park RD, Lewistown, PA.

C&D COMPONENT	ESTIMATED AVERAGE TIPPING FEE CHARGED BY RECYCLING FACILITIES PER TON	ESTIMATED AVERAGE COST TO RECYCLE PER TON	AVERAGE SALE PRICE OF RECYCLED MATERIAL WITH HIGH MOISTURE CONTENT (WOOD CHIPS) PER TON	AVERAGE SALE PRICE OF RECYCLED MATERIAL WITH LOW MOISTURE CONTENT (WOOD CHIPS) PER TON	ESTIMATED AVERAGE SALE PRICE OF RECYCLED MATERIAL (WOOD CHIPS) PER TON
WOODS	$31.00	NA	$18.50	$45.00	$31.75

Source: Miller's Wood Recycling, Industrial Park RD, Lewistown, PA, 2010.

Data on C&D Wastes Recycling Obtained from David Geppert Recycling, Inc., Wayne Ave., Philadelphia, PA.

C&D COMPONENT	ESTIMATED AVERAGE TIPPING FEE CHARGED BY RECYCLING FACILITIES PER TON	ESTIMATED AVERAGE COST TO RECYCLE PER TON	ESTIMATED AVERAGE SALE PRICE OF RECYCLED MATERIAL PER TON
COPPER	NO TIPPING FEE	$2.00	$3.20
ALUMINIUM	NO TIPPING FEE	$0.50	$0.85
YELLOW BRASS	NO TIPPING FEE	$1.00	$2.00
RED BRASS	NO TIPPING FEE	$1.40	$2.35
LEAD	NO TIPPING FEE	$0.20	$0.45
ALUMINIUM/COPPER	NO TIPPING FEE	$0.50	$1.45
		Average Cost = $0.93	**Average Price = $1.72**

Source: David Geppert Recycling, Inc., Wayne Ave., Philadelphia, PA, (www.geppertrecycling.com), 2010.

APPENDIX B continues

DATA ON C&D WASTES RECYCLING UTILIZED IN THE STUDY AND THEIR SOURCES

Data on C&D Wastes Recycling Obtained from US Environmental Protection Agency Publication*.

C&D COMPONENT	ESTIMATED AVERAGE TIPPING FEE CHARGED BY RECYCLING FACILITIES PER TON	ESTIMATED AVERAGE COST TO RECYCLE PER TON	ESTIMATED AVERAGE SALE PRICE OF RECYCLED MATERIAL (ASPHALT AGGREGATE) PER TON
Asphalt Roof Shingles	$30-$34	$30.00	Not Available

* The data were obtained by EPA in 1998.
Source: EPA 2009B.
(http://www.epa.gov/osw/conserve/rrr/imr/cdm/pubs/roof_br.pdf), 2009.

Data on C&D Wastes Recycling Obtained from New Jersey Department of Environmental Protection Publication*

C&D COMPONENT	ESTIMATED AVERAGE COST OF DISPOSAL PER TON	ESTIMATED AVERAGE COST TO RECYCLE PER TON
ASPHALT DEBRIS	$75.00-$98.00	$5.70
CONCRETE RUBBLE	$75.00-$98.00	$4.85
USED BRICKS/BLOCKS	$75.00-$98.00	$5.49
TREES & STUMPS	$75.00-$98.00	$37.69
WOOD SCRAP	$75.00-$98.00	$46.43

* The data was obtained by NJDEP in April 2004.
Source: NJDEP, Trenton, New Jersey,
(http://www.state.nj.us/dep/dshw/recycling/builderinfo.htm), 2005.

APPENDIX C

ESTIMATED ANNUAL QUANTITY OF CONSTRUCTION AND DEMOLITION WASTES DISPOSED IN PENNSYLVANIA IN 2009

ESTIMATED ANNUAL QUANTITY OF CONSTRUCTION AND DEMOLITION WASTES DISPOSED IN PENNSYLVANIA IN 2009

NUMBER OF COUNTY	COUNTY	QUANTIY OF C&D DISPOSED IN TONS	PERCENTAGE BY TOTAL QUANTITY DISPOSED	NUMBER OF COUNTY	COUNTY	QUANTIY OF C&D DISPOSED IN TONS	PERCENTAGE BY TOTAL QUANTITY DISPOSED
1	ADAMS	7736.1	0.7%	35	LACKAWANNA	18321.2	1.7%
2	ALLEGHENY	180863	16.9%	36	LANCASTER	66960.8	6.3%
3	ARMSTRONG	3246.9	0.3%	37	LAWRENCE	246.4	0.0%
4	BEAVER	5258.5	0.5%	38	LEBANON	12879.9	1.2%
5	BEDFORD	6564.6	0.6%	39	LEHIGH	18308	1.7%
6	BERKS	14001.8	1.3%	40	LUZERNE	7815.2	0.7%
7	BLAIR	7461.8	0.7%	41	LYCOMING	5790.3	0.5%
8	BRADFORD	8262	0.8%	42	MCKEAN	3680.7	0.3%
9	BUCKS	33524.8	3.1%	43	MERCER	380.8	0.0%
10	BUTLER	12359.8	1.2%	44	MIFFLIN	99.8	0.0%
11	CAMBRIA	8476.4	0.8%	45	MONROE	23578.9	2.2%
12	CAMERON	142.9	0.0%	46	MONTGOMERY	85006	7.9%
13	CARBON	899.5	0.1%	47	MONTOUR	1487.4	0.1%
14	CENTRE	78.9	0.0%	48	NORTHAMPTON	35594.3	3.3%
15	CHESTER	82556.4	7.7%	49	NORTHUMBERLAND	3941.4	0.4%
16	CLARION	213.2	0.0%	50	PERRY	3119.5	0.3%
17	CLEARFIELD	6408.9	0.6%	51	PHIILADELPHIA	56577	5.3%
18	CLINTON	4459.2	0.4%	52	PIKE	547.4	0.1%
19	COLUMBIA	6705.4	0.6%	53	POTTER	618.9	0.1%
20	CRAWFORD	1489.4	0.1%	54	SCHUYLKILL	6627.9	0.6%
21	CUMBERLAND	45801	4.3%	55	SNYDER	1095.4	0.1%
22	DAUPHIN	36429.8	3.4%	56	SOMERSET	6738.4	0.6%
23	DELAWARE	340.9	0.0%	57	SULLIVAN	1603.7	0.1%
24	ELK	5362.3	0.5%	58	SUSQUEHANNA	223	0.0%
25	ERIE	26070.5	2.4%	59	TIOGA	2056.1	0.2%
26	FAYETTE	13573.5	1.3%	60	UNION	2444	0.2%
27	FOREST	0	0.0%	61	VENANGO	422.8	0.0%
28	FRANKLIN	20884.5	2.0%	62	WARREN	1098.4	0.1%
29	FULTON	1139.5	0.1%	63	WASHINGTON	30408	2.8%
30	GREENE	7025.3	0.7%	64	WAYNE	4610.1	0.4%
31	HUNTINGDON	1068.8	0.1%	65	WESTMORELAND	51807.5	4.8%
32	INDIANA	14509.9	1.4%	66	WYOMING	1168.1	0.1%
33	JEFFERSON	1853.2	0.2%	67	YORK	50112	4.7%
34	JUNIATA	27.2	0.0%	**TOTAL =**		**1,070,165.2**	**100.0%**

Source: PADEP 2010 (http://www.portal.state.pa.us/portal/server.pt?open=514&objID=589667&mode=2)

APPENDIX D

ESTIMATED AVERAGE TIPPING FEES CHARGED AT C&D WASTES RECYCLING FACILITIES

Location	ESTIMATED AVERAGE TIPPING FEES CHARGED AT RECYCLING FACILITIES FOR THE C&D WASTE COMPONENTS ($/TON)								The Year Unit Cost Of Recycling Was Estimated	Source Of Information
	Used Asphalt	Used Concrete	Used Bricks & Blocks	Combined Asphalt/ /Concrete/ Brick& Block Debris	Used Wood	Metal Scraps	Drywall scraps	Roofing Shingles		
North East US (Including Pennsylvania)	NA	NA	NA	NA	NA	NA	NA	32.00	1998	From Roof To Roads, EPA 2009B
Pennsylvania (Philadelphia)	NA	NA	NA	NA	NA	NA	NA	47.42	2010	Based on 1998 data from EPA 2009B above; Using Sept. 2010 & Sept. 1998 ENR Average Construction Cost Index (8835.9/5963).
Pennsylvania (Philadelphia)	2.00	2.00	2.00	2.00	NA	NA	NA	NA	2010	Winzinger Recycling, Delaware & Allegheny Ave., Philadelphia, PA.
Pennsylvania (Reinholds)	NA	NA	NA	NA	NA	NA	25.00	NA	2010	USA Gypsum, Texter Mountain Road, Reinholds, PA.
Pennsylvania (Philadelphia)	NA	NA	NA	NA	NA	0.00	NA	NA	2010	David Geppert Recycling, Inc., Wayne Ave., Philadelphia, PA
Pennsylvania (Lewistown)	NA	NA	NA	NA	31.00	NA	NA	NA	2010	Miller's Wood Recycling, Industrial Park RD, Lewistown, PA.
Average Tipping Fees Charged at Recycling Facilities in Pennsylvania.	**2.00**	**2.00**	**2.00**	**2.00**	**31.00**	**0.00**	**25.00**	**47.00**	**2010**	**Calculated Based on 2010 Estimates in Pennsylvania Above.**

NA = Not Available.

APPENDIX E

ESTIMATED AVERAGE UNIT COST OF RECYCLING C&D WASTE COMPONENTS

Location	ESTIMATED AVERAGE UNIT COST OF RECYCLING C&D WASTE COMPONENTS ($/TON)								The Year Unit Cost Of Recycling Was Estimated	Source Of Information
	Asphalt to Asphalt Aggregates	Concrete to Concrete Aggregates	Bricks & Blocks to Brick & Block Aggregates	Combined Asphalt/ /Concrete/ Brick/ Block to Aggregates	Wood to Wood Chips	* Metals to Metals	Drywall to Agric. Products	Roofing Shingles to Asphalt Aggregates		
New Jersey (Trenton)	5.70	4.85	5.49	NA	46.43	NA	NA	NA	2004	N.J Dept. of Solid & Hazardous Waste, Trenton, NJ.
New Jersey (Trenton)	7.24	6.16	6.97	NA	58.97	NA	NA	NA	2010	Based on 2004 data from NJ Dept. of Solid & Hazardous Waste above; Using Sept. 2010 & April 2004 ENR Average Construction Cost index (8835.9 /6957.0).
North East US (Pennsylvania included)	NA	NA	NA	NA	NA	NA	NA	30.00	1998	From Roof To Roads, EPA 2009B
Pennsylvania (Philadelphia)	NA	NA	NA	NA	NA	NA	NA	44.45	2010	Based on 1998 data from EPA 2009B above; Using Sept. 2010 & Sept. 1998 ENR Average Construction Cost Index (8835.9/5963).
Pennsylvania (Philadelphia)	4.00	4.00	4.00	4.00	NA	NA	NA	NA	2010	Winzinger Recycling, Delaware & Allegheny Ave., Philadelphia, PA.
Pennsylvania (Reinholds)	NA	NA	NA	NA	NA	NA	15.00	NA	2010	USA Gypsum, Texter Mountain Road, Reinholds, PA.
Pennsylvania (Philadelphia)	NA	NA	NA	NA	NA	0.93	NA	NA	2010	David Geppert Recycling, Inc., Wayne Ave., Philadelphia, PA
Average Unit Cost of Recycling in Pennsylvania & Its Nearby Surroundings	**5.62**	**5.08**	**5.49**	**4.00**	**58.97**	**0.93**	**15.00**	**44.50**	**2010**	**Calculated Based on 2010 Estimates in Pennsylvania & Its Nearby Surroundings Above.**

* Only non-ferrous metals are considered since steel recycling has already been a highly profitable business with many recycling facilities.

NA = Not Available.

APPENDIX F

ESTIMATED AVERAGE UNIT PRICE OF RECYCLED MATERIALS FROM C&D WASTE COMPONENTS IN PENNSYLVANIA

LOCATION	ESTIMATED AVERAGE UNIT SALE PRICE OF RECYCLED MATERIALS FROM C&D WASTE COMPONENTS ($/TON)							THE YEAR UNIT COST OF RECYCLING WAS ESTIMATED	SOURCE OF INFORMATION
	Asphalt Aggregates	Concrete Aggregates	Bricks & Blocks Aggregates	Combined Asphalt/ Concrete/ Brick & Blocks Aggregates	Wood Chips	* Metals	Gypsum Agric. Products from Drywalls		
Pennsylvania (Philadelphia)	6.00	6.00	6.00	6.00	NA	NA	NA	2010	Winzinger Recycling, Delaware & Allegheny Ave., Philadelphia, PA.
Pennsylvania (Reinholds)	NA	NA	NA	NA	NA	NA	20.00	2010	USA Gypsum, Texter Mountain Road, Reinholds, PA.
Pennsylvania (Philadelphia)	NA	NA	NA		NA	1.72	NA	2010	David Geppert Recycling, Inc., Wayne Ave., Philadelphia, PA
Pennsylvania (Lewistown)	NA	NA	NA	NA	31.75	NA	NA	2010	Miller's Wood Recycling, Industrial Park RD, Lewistown, PA.
Average Unit Price of The Recycled Materials from C&D Components in Pennsylvania.	**6.00**	**6.00**	**6.00**	**6.00**	**31.75**	**1.72**	**20.00**	**2010**	**Calculated Based on 2010 Estimates in Pennsylvania Above.**

* Only non-ferrous metals are considered since steel recycling has already been a highly profitable business.
NA = Not Available.