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Re-Engineering a Trash/Recycling Collection Vehicle Based on Challenging Customer Requirements

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Based on Challenging Customer Requirements

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ABSTRACT

Engineering design starts with the definition of design requirements. These requirements define the design problem and must be satisfied for a solution to be acceptable. While many design methodologies exist for defining design requirements, none presently provides a systematic approach for designers to challenge requirements. Yet, Pahl and Beitz, Hazelrigg, and Suh all argue that a designer should continually question the need for each requirement and refine them as the product evolves. Thus, there exists a need to develop a comprehensive method that enables a designer to verify, review/question, and revise requirements throughout the design process. This research uses the design of a combined trash and recycling collection vehicle for Environmental America Inc. (EAI) as a case study to illustrate the positive impact of challenging customer requirements, offer examples of why requirements should be challenged, and describe the successful process used. Two unique design concepts are compared and the catalyst for challenging requirements is created when the seemingly superior concept does not satisfy one of the design requirements. The process of challenging requirements results in the development of three guiding principles. Three concepts, physical testing, defining more customers and refining their needs, and tracing a requirement to its original design decision, form the basis for the development of a systematic design method. Ultimately, this thesis provides the foundation for the development of a formal design

method to challenge requirements that can be adopted to different types of design problems and accepted by both academia and industry.

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DEDICATION

To my loving wife Sasha. I could not have done this without your sacrifice and continued support.

TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

Often, it appears that the success of an engineering design solution necessitates challenging customer requirements, yet there exists no specific tool which the designer can use to question and refine the specified requirements. This thesis introduces the idea of challenging customer requirements, providing evidence of its effectiveness through a multi-year case study on the development of a combined trash and recycling collection vehicle. This leads to the identification of a need for a formal design method or tool, the actual development of which is defined out of scope for this research. The specific case study that is used to justify the need to challenge requirements is based on the Environmental America Incorporated (EAI) sponsored engineering design project for 2005-2007.

Background

Environmental America Incorporated (EAI) is an emerging recycling company based in Greenwood, South Carolina, that plans to revolutionize the waste collection process through the use of a combined municipal solid waste (MSW) and recyclable material collection vehicle. The recyclables and MSW are collected, processed, and stored on-board the vehicle. MSW is compacted for off-loading at a landfill and recyclables are shredded, crushed, or baled for distribution to recycling centers. The company plans to focus initially on residential curbside collection in order to prove the viability of their collection vehicle. EAI plans to use the vehicle as an instrument for applying lean manufacturing principles to the curbside collection process in hopes of making the flow of recyclable material from collection to distribution more efficient.

Improving the efficiency of the collection and handling of recyclable material continues to become increasingly more important in order to meet US Environmental Protection Agency (EPA) regulations, such as those set forth in the Resource Conservation and Recovery Act[1] (RCRA). One of the regulations EAI is most interested in is the mandate of a 35% recycling rate as they envision their collection vehicle having the potential to realize a recycling rate as high as 70%. In order to understand how EAI plans to effectively "streamline" the curbside collection process, we need to understand the basic lean manufacturing principles used to analyze the current process before examining the process proposed by EAI

Lean Manufacturing

The application of lean manufacturing principles has improved the production flow of manufacturing companies across the globe. An emerging recycling company has proposed a revolutionary curbside collection process based on the use a combined waste collection vehicle and the application of lean manufacturing principles.

Manufacturing companies around the world and throughout all industries are shifting from the traditional system of mass production to a new system of production called Lean Manufacturing; a system which focuses on improving the production flow by eliminating waste (Carreira, 2004). Through the implementation of lean principles, companies are reducing waste and streamlining production and material flow within their manufacturing facilities. Additionally, much of the scrap material generated during production and many of the products themselves are recycled; further eliminating waste. However, many of the recycling agencies which service these facilities have failed to reduce the "waste" in the collection and processing of these recycled materials. Thus, the overall flow of material from product creation, to extinction, to reprocessing is flawed.

Companies practicing lean manufacturing focus on improving production flow by eliminating waste, which encompasses anything that gets in the way of smooth flow. In 2003 the EPA conducted a study examining the relationship between lean manufacturing and the environment. They found that lean manufacturing produces an operational and cultural environment that is highly conducive to waste and pollution prevention by minimizing material use and scrap, as well as reductions in water, chemicals, and energy (EPA, 2003). Additionally, the EPA found that lean manufacturing could be leveraged to produce additional environmental improvement through a greater understanding of environmental risk and product life cycle considerations.

If the practice of lean manufacturing is conducive to waste and pollution prevention, then how come the principles have not been implemented by the companies which collect and recycle this waste? One answer may be that the waste collection programs are simply resisting change; the same reason many manufacturing companies have been slow to employ lean manufacturing principles. Another possibility is that an

[1] http://www.epa.gov/rcraonline accessed May 03, 2006

effective method for implementing lean principles has not yet been developed. Regardless of the reason, it is clear that lean manufacturing has a positive impact the environment and business operations. At The Illinois Manufacturing Extension Center's recent conference entitled "2004 Manufacturing Matters!"

> The Manufacturing Performance Institute (MPI), provided compelling evidence that embracing lean pays off. The most recent results of its joint annual survey of manufacturers with Industry Week showed that a plant's median return on invested capital (ROIC) increases when it adopts lean manufacturing. In fact, plants that have implemented lean manufacturing have a median ROIC of 17% while plants that have yet to pursue any methodology only have a median ROIC of 10%. (Katrina, 2004)

One company which realizes the potential positive environmental and economical impact of the lean manufacturing methodology on recycling collection and processing is Environmental America Incorporated.

Lean Manufacturing Principles

Lean manufacturing is a systematic approach to identifying and eliminating waste through continuous improvement of production flow. Any activity that does not add to the market form or function of the product (things for which the customer is willing to pay) is classified as a non-value added activity, or the "wastes" that lean seeks to eliminate. Value-added activities are those which transform the product into something the customer wants or is willing to pay for. In manufacturing this is generally a physical transformation of the product to conform it to customer expectations. Lean manufacturing focuses on eliminating non-value added activities from a company's processes while streamlining value-added activities.

In the traditional mass production system, production flow improvements focus on reducing the time of value-added activities by increasing the efficiency of individual machines or personnel on the assembly line. These value-added improvements, while beneficial, have a minor impact on the overall lead time because value-added activities comprise only a small portion of the total lead time, see Figure 1.1. Lead time is defined as the amount of time that is required to meet a customer request or demand. Similar to the approach of the mass production system, lean manufacturing also seeks to eliminate waste from the production flow in the form of value-added activities. However, the primary focus of lean is to eliminate or reduce the time associated with non-value added activities. The reduction of non-value added activities has a significant impact on lead time because it comprises the majority of the total lead time. According to the Iowa State University Facilities Planning and Management, "typically 95% of all lead time is non-value added" (Iowa State University, 2005)

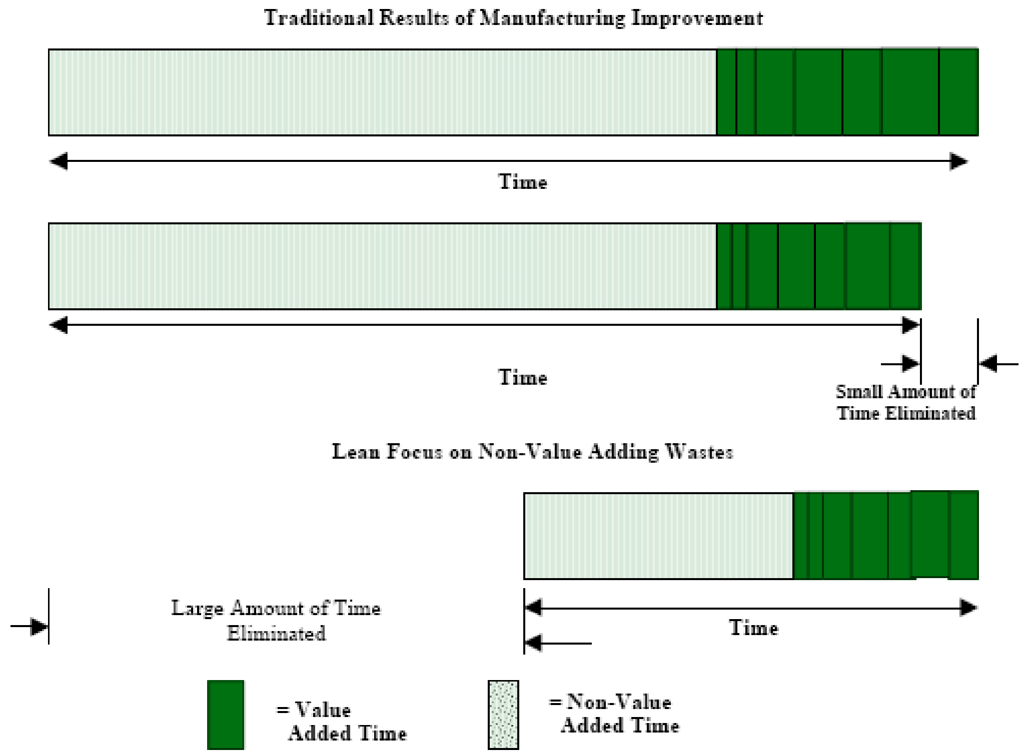


Figure 1.1 - Traditional vs. Lean Manufacturing Improvements (from University of Michigan, 2000)

The significant reduction in lead time by eliminating waste in the form of non-value added activities demands a closer look. Often manufacturers see non-value added activities as necessary evils of doing business, but lean manufacturing views them as "wastes" that should and can be eliminated. However, one must first obtain a more clear understanding of exactly what constitutes waste in order to determine how best to eliminate it.

The Toyota Production System (Ohno, 1988), considered by many to be the pioneering system of what is now lean manufacturing, separates waste into seven distinct categories: overproduction, inventory, defects, processing, transportation, waiting, and motion. Recently, much of the manufacturing community has adopted an eighth waste, which is commonly classified as people, or more specifically, their underutilization. These eight wastes are briefly described by the Illinois Manufacturing Extension Center (Illinois Manufacturing Extension Center, 2005) as follows:

> 1. **Overproduction**: This is probably the most deceptive waste. It simply is making more products earlier and faster than the next process requires. In all cases, overproduction leads to unneeded inventory. Overproduction usually is deliberate to cover up quality deficiencies, equipment breakdowns, inadequate employee training, long process set-up and unbalanced workload.
>
> 2. **Inventory**: This waste is any supply in excess of a one-piece flow through the process, including work in process and finished goods. Holding inventory costs money—roughly 25 percent of the value of the inventory if held for a year.
>
> 3. **Defects**: This is a major waste that includes material, labor, machine hours, inspecting, sorting or rework. Its causes can be inadequate training, weak process control, deficient maintenance and/or incomplete engineering specifications.
>
> 4. **Processing**: This waste is effort that adds no value from the customer's viewpoint. It can include extra or incorrect inspections, extra copies of paperwork and over or redundant processing "just-in-case." Expediting processing because of failing to meet schedule also is a waste.
>
> 5. **Transportation**: Moving materials in the manufacturing process can add costs, but no value. Not only does the act of transporting add to costs, it also typically involves using expensive equipment. Further costs are space, racking and the people and systems needed to track the material.
>
> 6. **Waiting**: This includes all idle time, such as waiting for parts from up-stream operations and waiting for tooling, set-ups and instructions. Waiting for workers generally is of greater concern than machine use.

7. **Motion**: Any people and/or machine activity that doesn't add value to the product is considered waste. Its symptoms include time looking for tools, extra product handling, walking and product arrangement, stacking, etc. Causes include poor plant layout and workplace design, inadequate training, weak processing and constant schedule changes to reduce on-time delivery problems.

8. **People**: Factors such as company culture, hiring practices, management styles, turnover rates and morale all contribute to this waste—not using the employees' abilities to their fullest potential.

Identifying the different "wastes" in a given manufacturing process allows the manufacturer to develop a plan for effectively eliminating them. This was the approach adopted by EAI in order to streamline the municipal solid waste (MSW) and recycling collection process. Analysis of the current collection process revealed many non-value added activities which could be eliminated, as well as value-added activities which could be made more efficient. These findings were used to develop the combined collection vehicle, which enabled EAI to propose a new and more efficient process for curbside collection.

<u>Method for Analyzing Collection Processes</u>

The current residential waste collection process consists of the curbside pickup of MSW and recyclable material. This process utilizes separate MSW and recycling collection vehicles, generally with multiple operators for each truck. In order to ascertain the areas for improvement in the current collection process; it was evaluated based on lean manufacturing principles. A simplified model of the curbside collection process was analyzed from a value-added versus non-value added lean manufacturing perspective. This method successfully identified the "wastes" in the collection processes. It is important to note that the collection process varies from state to state and even between different counties of a particular state, based on the programs and facilities in place.

Analysis of the Recycling Collection Process

Typically, the curbside recycling collection process consists of a collection vehicle with either one or two operators. The population of the city or municipality serviced by the collection agency dictates the number of collection vehicles which must be in operation in order to service all of the households. Figure 1.2 is representative of a typical curbside recycling collection process.

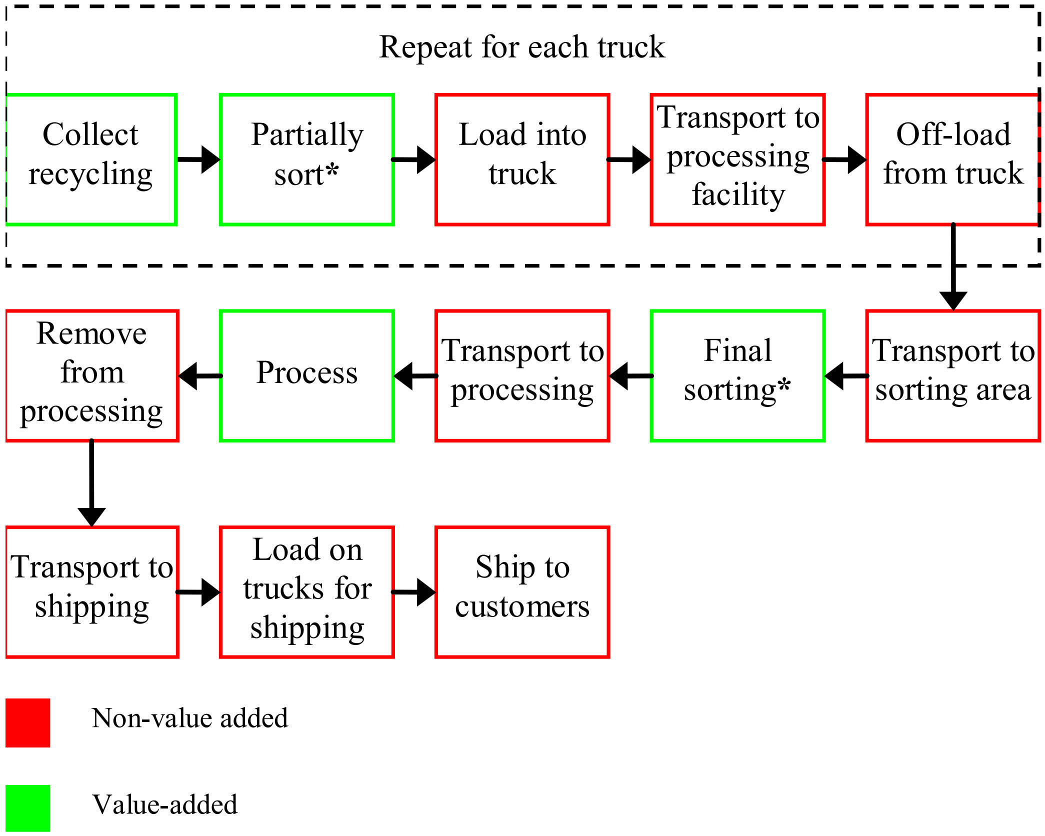


Figure 1.2 - Typical Recycling Collection Process

As noted in the figure, value-added steps are depicted in green and non-value added steps in red. The first five steps of the process are conducted each day by all trucks in service, with the first three steps: collection, partially sorting, and loading into the truck, repeated for each household on a given trucks service route.

Initially, the recyclable material is collected and partially sorted at the curbside before it is loaded into the truck. The physical collection of the recyclable material is a value-added activity because it is something the customer is willing to pay for. In this case the customer is the homeowner who pays for the service of removing their recyclables. Next, the recyclable material is partial sorted, which usually consists of separating the material into broad categories such as paper, plastics, glass, and metals. This is a value-added activity because the company buying the recyclable material will only purchase it if it has been separated into specific individual categories with minimal contamination. The individual categories desired for purchase and the acceptable amount of contamination varies among recycling companies. This partial sorting is the first of two sorting steps, denoted by asterisks, which help to ensure that the material is properly separated with acceptable levels of contamination.

After the material has been sorted it is loaded into the truck, which is the first non-value added step or "waste" of the process. This waste falls under the previously defined classification of Motion because it consists of extra product handling that does not add value to the product. Next, the material is transported to the processing facility, which adds no value. The following two steps of off-loading the material from the truck and transporting it to be sorted are additional Motion and Transportation wastes. Therefore, these four non-value added steps in the process involve only two types of waste: Motion and Transportation. The material is off-loaded at a Material Reclamation Facility (MRF), where it is then transported to an area within the facility for sorting, typically via a conveyor belt.

The final sorting of the recyclable material takes place at the MRF and is a value-added step which ensures the material is properly separated into categories which the recycling companies are willing to pay for. In this process, plastics are separated into high-density polyethylene (HDPE) and polyethylene terephthalate (PET or PETE), some common examples of each are shown in Figure 1.3 and Figure 1.4.

Figure 1.3 - Common PETE Containers (from Campus Advantage[2])

PET or PETE containers are one of the easiest materials to recycle. Most plastic containers are made of this type of plastic and common examples include soda bottles, water bottles, and food containers. HDPE is generally a more rigid and durable plastic that is commonly used for milk jugs, laundry detergents and motor oil.

[2] http://campusadv.com/green/?tag=recycling accessed October 26, 2009

Figure 1.4 - Common HDPE Containers (from Campus Advantage[2])

In addition to separating plastics, the MRF also separates glass into individual colors, and metals into ferrous and non-ferrous. This is a costly and time-consuming process, which typically consists of expensive machinery and requires a large number of personnel as shown in Figure 1.5.

Figure 1.5 - Sorting of Recyclable Material (from Leposky, 2005)

Although the final sorting of the recyclable material is a value-added process, it is a potential People waste which could be streamlined by restructuring the process such that it requires less employees. After sorting, the material is transported across the facility to be processed; yet another Transportation waste. The processing of the material is the final value-added step and it consists of transforming the material into a state which the customer or recycling company desires. Typically, this consists of bailing, crushing or shredding the material.

The remaining steps encompass removing the processed material, transporting it to the shipping area of the facility, loading it onto a truck for shipping and delivering it to the customer. These non-value added steps are further Motion and Transportation wastes. Thus, the entire process consists of four value-added steps and nine non-value added steps which are classified as Motion and Transportation wastes. Therefore, the

EAI combined collection vehicle focuses primarily on eliminating these two types of wastes and streamlining material sorting and processing.

Analysis of the MSW Collection Process

The curbside MSW collection process consists of a refuse collection vehicle with either a two or three man crew. Based on the population of the city or municipality, multiple refuse vehicles are operated in order to service all of the households. A typical daily curbside MSW collection process is illustrated in Figure 1.6. Similar to the collection of recyclables, the collection of MSW is a value-added activity because the homeowner or customer pays for the collection service. Additionally, off-loading the waste into the landfill is a value-added activity. Although the collection companies or municipalities are charged fees to deposit waste in the landfill, the process is value-added because the customers are the residents whose taxes pay for the MSW to be deposited in the landfill.

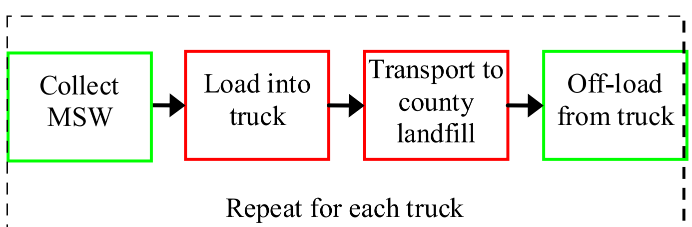


Figure 1.6 - Typical MSW Collection Process

However, loading the waste into the collection truck and transporting it to the county landfill are non-value added processes; Motion and Transportation wastes.

The curbside collection of MSW is a relatively lean process with non-value added activities comprising only 50% of the process. With a relatively low percentage of non-value added steps, it may not be feasible to eliminate them from this process. However, it may be possible to reduce the time of these steps. In this process, each refuse truck in service travels to the landfill and back at the end of each day's route. Thus, the amount of time associated with this Transportation waste is significant. Additionally, the frequency of trips to the landfill increases gasoline or energy consumption as well as vehicle wear and required maintenance. Therefore, reducing the number of refuse trucks traveling to the landfill each day would not only reduce the time associated with this non-value added activity, but would create an energy cost savings and potentially extend the service life of the collection vehicles. EAI hopes to realize this savings by proving that three of their combined collection vehicles can replace four standard trucks (2 refuse and 2 recycling).

Proposed Municipal Solid Waste and Recycling Collection Process

Analysis of the curbside MSW and recycling collection process from a lean manufacturing standpoint revealed numerous non-value added activities which can be eliminated or reduced and value-added activities which can be made more efficient. EAI has proposed a collection process which will improve the overall material flow through the use of a "collection vehicle specializing in the combined collection of raw waste and recyclable waste" (EAI, 2004). This collection vehicle, combined with localized, low-impact material off-loading facilities has the potential to revolutionize the curbside collection process.

EAI has proposed using a single vehicle to collect both MSW and recyclable material, which will significantly reduce the non-value added activities or "wastes" of the recycling collection process and streamline the sorting and processing of the recyclable material. This is realized in part by the vehicles unique design which allows for the complete sorting and processing of the recyclable material onboard the truck. The single vehicle performs the tasks of two of the conventional vehicles currently utilized, which realizes labor, maintenance, energy, and capital savings.

The curbside collection process proposed by EAI is depicted in Figure 1.7, where the first phases of both the recycling and MSW collection processes are carried out by the same vehicle. Due to the combined nature of the truck, the MSW collection is conducted concurrently with the recyclable collection, sorting, and processing, reducing the overall lead time of these value-added steps. Furthermore, the two disconnected sorting steps of the current process are replaced with one step conducted by two operators at the curbside, streamlining the processing. This also reduces the People Waste identified in the final sorting step of the current process by more efficiently utilizing fewer employees to complete the same task. However, since the material is only sorted once in this process, it will be very important to train and motivate operators in order to avoid contamination errors.

The on truck sorting and processing eliminates many of the Motion and Transportation wastes revealed in the current process. The processing of the recyclable material onboard the vehicle makes loading the material into the truck a value-added process because it directly results in transforming the material into something the recycling firm is willing to purchase. Due to the on-vehicle processing, the recycled material no longer has to be transported to a MRF for sorting and processing because it is removed from the truck in its final state. Thus, the material is off-loaded from the collection vehicle and either loaded directly on to a transport truck where it awaits final shipping to a recycling firm or stored at a local, low-impact facility until a transport truck is available. This process is repeated for multiple collection vehicles until the transport trucks are full, at which point they are sent out to the company purchasing the recycled material.

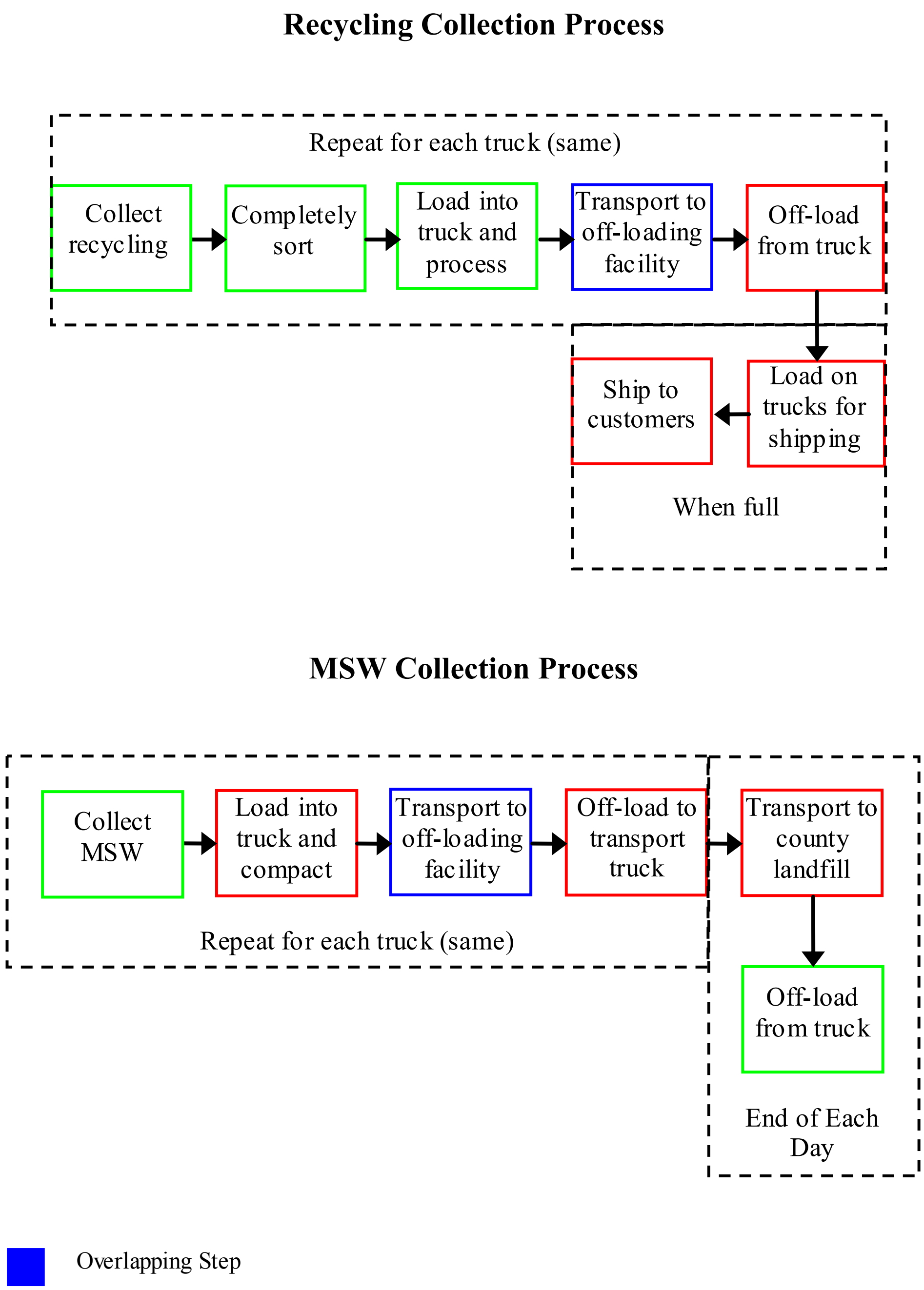


Figure 1.7 - Proposed MSW and Recycling Collection Process

The collection process proposed by EAI consists of multiple local, low-impact off-loading facilities as opposed to one central county facility. Essentially, each city or municipality would have their own off-loading location. These facilities require less than an acre of land and would consist of a small building with a loading dock. The only material stored in the building is recycled material which is not odorous and would only be stored for a short period of time, until a transport truck is available for loading. Additionally, forklifts are the only equipment needed to transfer material from the collection vehicles to the transport trucks. Thus, these facilities will have a low-impact on the city or municipality in which they are located.

The close proximity of the off-loading facilities to the residential routes serviced by the collection vehicles significantly reduces the Transportation Waste associated with the current recycling process. Reducing the distance between the service route and the off-loading facility not only saves time, but reduces gasoline or energy consumption in addition to decreasing the wear on the vehicle and thus the required maintenance. An additional benefit of the local facilities is that each city or municipality is able to generate their own revenue from the sale of recyclables as opposed to the county as a whole.

In the proposed MSW collection and handling process, the waste is off-loaded from curbside collection vehicles at the same facility as the recyclables and loaded into a larger transport truck. At the end of each day, the MSW is transported to the landfill and dumped. This reduces the frequency in which the raw waste is transported. Instead of every truck in service transporting MSW to the landfill at the end of each day, only one or two trucks, dependent on the size of the municipality, are required to make this trip. This is a significant reduction in Transportation Waste, as this is typically a lengthy haul because landfills are usually located on the periphery of a county. By reducing the number of trucks going to the landfill, the daily energy consumption is decreased. This is beneficial from an environmental point of view as well as a financial standpoint as the cost of energy continues to rise. However, in order to realize this reduction in waste, two non-value added steps had to be added to the process, which is contrary to the goal of lean manufacturing.

The two non-value added steps added to the process consist of transporting the MSW to the off-loading facility and off-loading it into the transport truck which takes it to the landfill. These steps are necessary in order to realize the reduction in transportation to the landfill. The impact of these non-value added steps is mitigated by the fact that the collection vehicle must travel to the off-loading facility to empty the recycled material. Due to the combined collection process of the truck, the activity "transport to off-loading facility" overlaps between the recycling and MSW collection processes, as shown in Figure 1.7. Therefore, this activity is redundant and is essentially already accounted for in the recycling collection process. Thus, the only truly additional step in the process is transferring the MSW from the collection vehicle to the transport truck. This is easily accomplished with a forklift and can be conducted simultaneously with the off-loading of the recyclables. Therefore, the negative impact of these steps on the overall process is far less than the positive impact of reducing the number of vehicles traveling to the landfill.

EAI envisions the transfer of MSW from the collection vehicles to the transport trucks as the more efficient overall solution. Unfortunately, the current policies of most state and local governments will not allow the transfer of waste from one vehicle to another at a location central to collection vehicle routes, typically within city limits. In most cases, the transfer of waste can only be performed at licensed transfer stations that are outside the city limits, defeating much of the benefit. This is due primarily to the "Not In My Back Yard" or NIMBY syndrome (Portney, 1991). Thus, the proposed "lean" MSW collection process is a long-term goal that cannot be realized until the idea and use of local transfer stations becomes more widely accepted. Fortunately, policy hurdles were identified early in the design process and the first generation of the truck is being developed to integrate into the current collection process of transporting waste to the landfill via the collection vehicle. Therefore, most of the benefits of the combined collection vehicle can be realized immediately, with hopes of driving governmental policy changes that would allow a future generation vehicle to realize even greater savings (Troy, 2006).

While the proposed MSW and recycling curbside collection process reduces the number of non-value added activities and streamlines the value added activities, it also reduces the vehicle fleet for a given municipality. The EAI collection vehicle is being designed to service 350 households as opposed to the 500 households typically serviced by each of the separate refuse and recycling collection trucks currently in service. While this does not result in the optimal replacement of two vehicles with one, it is necessary in order to keep the size of the truck small enough to navigate neighborhood roads and most city streets. Essentially, three of the EAI combined collection vehicles replace four of the current vehicles: two refuse trucks and two recycling trucks. An example of a vehicle fleet which would service about 4000 houses a day is shown for the current curbside collection process and that proposed by EAI in Figure 1.8 below:

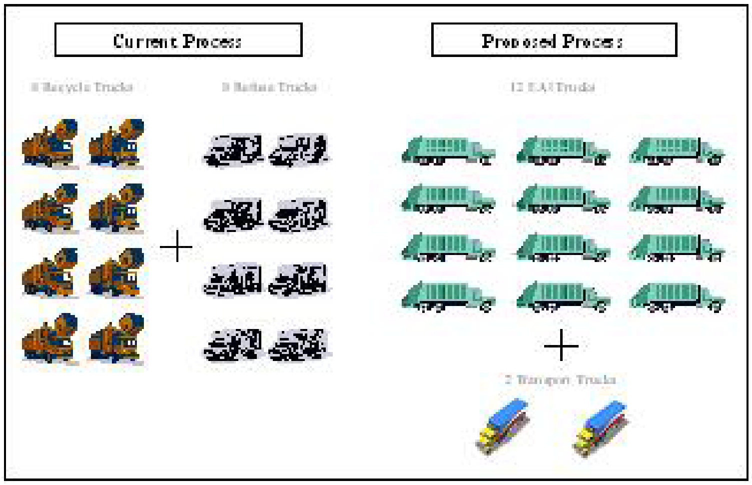


Figure 1.8 - Vehicle Fleet: Current vs. Proposed Curbside Collection Process

In this example, the proposed process replaces 16 collection vehicles with 12 collection vehicles and 2 transport trucks. This results in a savings in capital investment. Furthermore, fewer vehicles results in reduced energy consumption and required maintenance.

Combined MSW and Recycling Collection Vehicle

While manufacturing companies around the world are realizing the benefits of implementing lean manufacturing principles, the curbside collection process has been slow to change. However, with increasing EPA recycling mandates, the pressure on curbside collection companies to make changes is rising. Through the use of their combined collection vehicle, Environmental America Incorporated has developed a process with the potential to reduce many of the "wastes" associated with the residential collection of MSW and recyclable material. The use of this collection vehicle, along with local off-loading facilities, has the potential to streamline the value-added steps of the collection process and effectively eliminate non-value added activities. Additionally, it significantly reduces the number of trucks traveling to the landfill daily and thus the associated energy usage and cost. While this may not be the ultimate solution to eliminating "waste" from the curbside collection process, it is certainly a viable solution and a step in the right direction.

Significant research into the methods of processing the recyclables is necessary for the development of an efficient system. While there are many commercial processing solutions available on the market, the combination garbage and recycling truck poses a specific problem. There does not seem to be a commercial off-the-shelf system available that can satisfy the requirements of capacity, automation, segregation, and transportability that are associated with the curbside processing.

Based on a survey of current refuse and recycling truck manufacturers, there is currently only one company with a commercially-available, combined MSW and recycling collection vehicle: Heil Environmental[3], the worldwide leader in manufacturing of refuse and recycling collection vehicles. The Heil Rapid Rail Co-Collector "One Pass" Collection truck[4], see Figure 1.9, has the unique ability to collect MSW and recyclables in the same vehicle and store them in separate locations onboard. However,

[3] http://www.heil.com/ accessed October 27, 2009
[4] http://www.heil.com/products/rrailco.asp accessed October 27, 2009

the recyclable material collected must be stored co-mingled, which means it will have to be processed after unloading in the traditional fashion.

Figure 1.9 - Heil Rapid Rail Co-Collector Vehicle (from Heil[4])

The Co-Collector vehicle features two body compartments of equal size. One compartment is used to store recyclables, the other for MSW. Each compartment has an individual compactor, which is the only form of processing, and can be emptied separately. While the Co-Collector is a good first step in combined MSW and recycling collection, it is lacking the ability to separately store and uniquely process different types of recyclables. Most importantly, the truck is proof that there is a market for a combined collection vehicle.

Further investigation revealed a US patent for a "Separated Discards Carrier" that has the ability to collect MSW and recyclables in the same vehicle (US Patent 4,425,070. 1984 Jan 10.). According to the patent, the carrier would have the ability to collect newspaper, glass, and cans in addition to MSW. Unlike the Heil Co-Collector Vehicle, this carrier would separately store three categories of recyclables. Furthermore, the recyclables are able to be unloaded at a recycling center with little effort and no specialized equipment. The two biggest weaknesses of this design are the lack of recyclable processing and the inability to collect and store more than three different categories of recyclables. The recyclable storage volume appears relatively small, which coupled with the lack of onboard processing would limit the vehicles service and require it to unload frequently. Perhaps this is one of the reasons the vehicle was never put into production.

Environmental America Incorporated has further developed the idea behind these two vehicles and holds multiple patents related to their combined collection vehicle (US Patent 5,275,522. 1994 Jan 4., US Patent 5,511,687. 1996 April 30., US Patent 6,499,931 B1, 2002 December 31.). What is unique to the EAI vehicle is the use of onboard recycling processing and the ability to separately store more than three categories of recyclables. The EAI vehicle is able to store more individual materials, in larger quantities, due to the reduction in volume realized by the onboard processing. Once full, the recycled material can be offloaded from the truck and shipped directly to an individual recycling facility for final processing.

Figure 1.10 - EAI Prototype Combined Collection Vehicle

The EAI collection vehicle shown in Figure 1.10 is the company's fourth prototype to date. It is designed to be operated by three personnel. The truck contains a rear-located sorting table, depicted in Figure 1.11, where one operator collects and completely sorts the recyclables while loading them into small individual hoppers.

Figure 1.11 - Sorting Table and Hoppers

After the hoppers are full, a Programmable Logic Controllers (PLC) orchestrates the automated processing of the material in the hoppers. The hoppers are driven up to the top of the vehicle, where their contents are emptied through the bottom into larger storage bins. Before entering the storage bins, plastics are shredded, while glass, aluminum cans, and steel cans are crushed. In addition, the vehicle contains balers, located in the middle of the truck, where the second operator sorts paper and cardboard into individual baler bins, see Figure 1.12. The operator then controls two hydraulic rams that traverse the multiple bins and compact the material for efficient on-truck storage.

Figure 1.12 - Onboard Balers

The final operator, the driver, attaches the trash can to an automated side loader, which empties the waste into the truck where it is automatically compacted for increased storage capacity.

EAI joined with Clemson University to refine the collection vehicle and process with hopes of entering the market place in 2008. The company plans to apply this onboard processing concept to the future design of commercial waste collection vehicles for stadium events and high-rise apartments. Additionally, they envision future generations of the collection vehicle to have increased recycling storage volume and decreased MSW capacity as recycling programs are further developed. Ultimately, there combined collection vehicles could replace the standard trash and recycling trucks used across the country.

CHAPTER 2

CASE STUDY: EAI COMBINED COLLECTION VEHICLE (PROJECT OVERVIEW)

The objective of this research was to use the design of the EAI combined collection vehicle as a case study to illustrate the positive impact of challenging customer requirements, offer examples of why requirements should be challenged, and describe the successful process used. This research was centered on the complete ground-up redesign of the prototype combined recycling and waste collection vehicle previously developed by EAI as described in Chapter 1. The resulting participant-as-researcher case study stretched over a three year period and involved many facets of engineering, including design, analysis, and manufacturing, as well as numerous people ranging from undergraduate students to industry representatives.

Project Personnel

This project was headed by four Clemson University graduate students: Peter Johnston, Stuart Miller, Timothy Troy, and Eddie Smith (thesis author). Together, we formed a design team known as the Clemson Recycling In Truck Research (CRITR) development group, with each member having distinct roles and responsibilities. Johnston focused primarily on the design of the on-board material processing system, although he was also involved in the concept and embodiment design of other systems. Miller, who began his work on the project as an undergraduate student and later continued through graduate school, was responsible for the trash collection and compaction design. Troy was involved only in the early stages of the design process, where he assisted with requirements and concept generation. He focused mainly on the public policy issues of combined curbside collection. Smith's design responsibilities consisted of overall vehicle layout design and system integration.

In addition to the design team, the project involved other graduate and undergraduate students. Among the undergraduate students was Hunt Werner, who spent a semester on the project as an undergraduate researcher at Clemson University, assisting in the design of the trash compaction system. Additionally, undergraduate students from both the Spring 2005 and Fall 2005 Clemson University Mechanical Engineering Design (ME 401) classes participated in the research through student projects. The research also involved graduate students and faculty from the Automation in Design (AID) and Clemson Research in Engineering Design and Optimization (CREDO) laboratory groups. AID conducts research focused on automating the engineering design process and the CREDO group does work primarily in design methodology, optimization, and prototyping. Students and faculty from these research groups attended several presentations by the design team where they provided feedback and suggestions. The project was managed by Dr. Joshua D. Summers, Associate Professor of Mechanical Engineering. His roles included student advising, team management, design review participation, customer liaison, and conceptual development.

Industry representatives and employees and owners of EAI were involved to varying degrees throughout the redesign process. Representatives from different companies specializing in hydraulic rams, recyclable material processing, recyclable material bale strapping, and trash compaction were contacted via phone throughout the project in order to gain their expertise on the subject matter. Many of the companies contacted and the expertise elicited are listed in Table 2.1.

Table 2.1 - Company Expertise

COMPANY	EXPERTISE
Powell's Trash Service	Curbside collection industry practices and typical vehicle services and service intervals
Canusa Hershman Recycling Company	Definition of shredded plastic or regrind
Polychem USA	Definition of shredded plastic or regrind, recommendation regarding shredding vs. baling plastics
Evergreen Plastics	Acceptable PET plastic bale sizes, densities, and contamination, as well as bale pricing
United Plastics	Acceptable PET plastic bale sizes, densities, and contamination, as well as bale pricing
International Baler	Hydraulic baler ram sizing and industry bale densities, bale strap material type and size
Cross Hydraulics	Hydraulic baler ram design, sizing, and system requirements
C&M Baling Systems	PET plastic bale results using a hydraulic vertical down-stroke baler
Baletech	Current industry baler designs and capabilities
Harris Waste Management Group	Current industry baler designs and capabilities
Marathon Balers	Current industry baler designs and capabilities
Balemaster	Current industry baler designs and capabilities
The C.S. Bell Co.	Glass crusher capabilities and adaptation of hydraulic drive system
Wayne Engineering	Trash compactor design and capabilities
Nu-Life Environmental	Trash compactor design and capabilities
Ryerson	Steel and aluminum material availability and pricing
Mack Trucks	Vehicle chassis details, recommended drivetrain, power-take-off's, and availability
Freightliner Trucks	Vehicle chassis details, recommended drivetrain, power-take-off's, and availability
Peterbilt Trucks	Vehicle chassis details, recommended drivetrain, power-take-off's, and availability
Crane Carrier	Vehicle chassis details, recommended drivetrain, power-take-off's, and availability
Sterling Trucks	Vehicle chassis details, recommended drivetrain, power-take-off's, and availability

In addition to phone conversations, personal visits to Powell's Trash Service in Greenwood, SC and Nu-Life Environmental Incorporated in Easley, SC allowed the CRITR team to thoroughly observe trash and recyclable processing equipment and gain hands-on, real world working knowledge. Observing these vehicles and speaking with the company representatives helped the team to develop a better understanding of the residential curbside collection industry.

The team also worked closely with personnel from the Kite Hill Recycling Facility at Clemson University in Clemson, SC. This recycling facility services the Clemson campus and surrounding areas. When on loan from EAI, the prototype collection vehicle was stored at the facility. The employees provided large quantities of free recyclable material, such as plastic bottles and aluminum cans, for testing of the vehicles on-board processing equipment.

EAI President Billy Garrett, and Vice Presidents Chuck Kelly and Larry Aldridge were intimately involved in the project. They provided access to the vehicle prototype for testing, assisted with some of the tests, and traveled with the design team to meet with many of the industry representatives. Additionally, they supplied background data such as recycling collection volumes obtained from a test of 125 residential homes where they collected the residents recycling boxes. Moreover, they attended frequent design presentations and meetings where they were actively involved in making design decisions.

Project Organization

This project was organized like a typical industry design project, involving a client and a design team. The design team created concepts, conducted testing, detailed designs, and communicated with the client through official design reviews. Further, the design team used added resources of Clemson University students, both undergraduate and graduate, as well as several Clemson University professors. This allowed the team to obtain design critiques and prospective from people who are not familiar with the curbside collection industry, avoiding pre-conceived notions of how things should be done. It also enabled the team to explore many novel design concepts through the use of student design projects.

Two class based student design projects were carried out which involved the undergraduate students of Clemson University's Mechanical Engineering Design (ME 401) classes. This is a senior level class which focuses on design development, analysis, and assessment through the completion of two group design projects[5]. For each of the Spring 2005 and Fall 2005 semesters, these student design projects accounted for one of the three group projects. Typically, students worked in groups of three to five with a project lasting about five weeks.

The first student design project was conducted in Dr. Fadel's Spring 2005 ME 401 class. For this project, each student team was tasked with designing one of a series of on-truck recycling processing modules which could be incorporated into the EAI curbside collection vehicle. The modules needed to be capable of processing glass,

[5] http://www.ces.clemson.edu/me/studentinfo/undergrad/syllabus/ME401.pdf

plastic, metal, or paper residential waste depending on which project the design team was assigned, see Appendix F. Teams had to determine the recycling volume requirements for 350 households and define the final state in which the recycled material would be delivered to the reclamation facility. Additionally, they were required to specify module operational and manufacturing costs.

The second project was conducted in the Fall 2005 of ME401, also taught by Dr. Fadel. This project was more focused than the first and centered on the design of an onboard baling module for the EAI curbside collection vehicle. The goal was for the students to design a baling system capable of handling 46 ft^3 of unprocessed and unsorted paper as well 9 ft^3 of unprocessed cardboard, see Appendix G. The system needed to be capable of being loaded internal to the truck and had to provide any on-truck material storage necessary for the vehicle to service 350 households. Additionally, the system had to be safe to operate, use standard power and control systems, and be cost effective to manufacture, operate, and maintain. Students were also asked to provide justification for whether it was economically feasible to process paper and cardboard commingled. They were provided with access to the EAI prototype collection vehicle and encouraged to ask questions of the CRITR team. Ultimately, the students were expected to produce a complete drawing package with a bill of materials and assembly plan.

The student design projects provided the CRITR team with valuable data to discuss and evaluate. Perhaps the most important information was the design concepts generated from the projects. These concepts provided the design team with numerous different feasible ideas in a relatively short period of time. Furthermore, these concepts offered fresh perspective from those unfamiliar with the development history of the EAI collection vehicle and the curbside collection industry as a whole. Additionally, the recyclable material volume estimates developed by the students served as a validation for the 350 household volume projections.

This research project relied on a multitude of data which was compiled and analyzed. In addition to the student design project results, data was obtained in several different ways. Some of the most prevalent were test results, meeting notes, and communication with industry representatives. Additionally, each member of the research team kept a design journal where they documented their observations and self reflection throughout the entire design process. Information from design review meetings was also documented and communicated to the client in the form of memos and reports.

The project was structured and managed such that the research students, academic advisor, and the client closely collaborated throughout the design process. This was primarily accomplished through routine design review meetings. Meetings took place once every few weeks between the research students, Summers, and several representatives from EAI. The representatives from EAI included President Billy Garrett, Vice Presidents Chuck Kelley and Larry Aldridge, as well as consultant Gary Garrett. These meetings usually occurred in the evenings at Clemson Universities Fluor Daniel Engineering Innovation Building and lasted approximately two hours. However, some meetings took place at the company's offices in Greenwood, South Carolina. The primary purpose of the meetings was to discuss design concepts, present testing results, and make critical design decisions necessary to move the project forward.

In addition to the design review meetings with the client and academic advisor, several other meetings took place. Meetings were established with the client as needed to conduct testing with the prototype vehicle. These meetings took place at the EAI manufacturing facility in Greenwood, South Carolina, as well as the Kite Hill Recycling Facility at Clemson University. Weekly one-on-one meetings between the advisor/project manager and the individual graduate students were dedicated to both research advising and project management. Weekly CRITR team meetings focused on project progress, sub-system problems, and future work. Additionally, the design team members met together several times a week, often impromptu, to discuss a variety of different things, from test results to design decisions.

As with any collaborative project, communication was one of the most important aspects. This was primarily due to the large scale of the project, the conceptual nature of the design, and the numerous different people involved. Several different methods of written, verbal, and visual communication were used effectively throughout the project. Written agendas and brief memos were often prepared for design review meetings with the client in an effort to convey critical information and keep the meetings focused. In addition, short reports on findings or results were used to convey more in depth information to both the client and academic advisor. Visual communication was critical in conveying design concepts and for this; the design team relied heavily on three dimensional modeling. Interactive models created in SolidWorks[6] were used to illustrate design concepts during both design team meetings and meetings with the client.

[6] http://www.solidworks.com/ accessed October 29, 2009

Typically, these models were projected from a laptop onto a large screen for easy viewing and discussion. The design team also made extensive use of sketching with markers on erasable white boards during meetings to illustrate design elements. Communication was conducted face-to-face where ever possible, in the form of presentations, question and answer sessions, and group discussions. When direct communication was not available, the team relied on phone conversations, fax's, and emails.

This design project serves as the basis for this research studying the effects of challenging customer requirements. This project demonstrates, through specific examples, a motivation for and a method to applying simple challenging strategies that can have a positive impact on the project. The next chapter discusses requirements in the general design process, focusing on their role in design and limitations.

CHAPTER 3

REQUIREMENTS

A requirement represents a need which must be satisfied in order for something else to occur (Merriam-Webster, 2008). Note, in this case we are only concerned with product requirements; thus, we do not directly consider development time or cost. In the case of engineering design, requirements are the statements that engineers use to define problems. These statements identify critical attributes, characteristics, capabilities, or functions of the design in order to improve the understanding and focus of the designer (Young, 2001). They act as rules or guiding principles throughout the design process. Requirements are conditions which must be met, often referred to as constraints, in order for the design to be successful. Constraints are treated as immovable in engineering design and as such are used to reduce the complexity of the design process (Hazelrigg, 1996). Pahl and Beitz describe these types of requirements as *demands*, which must be satisfied or else the solution is not acceptable (Pahl and Beitz, 1996). Similarly, Suh defines constraints as something that must be met, typically bounding or limiting in effect (Suh, 1990). He separates constraints into two types, input constraints and system constraints. Input constraints are constraints in design specifications, where as system constraints are those imposed by the system or environment in which the design solution exists. For this research, requirements are defined as constraints that the design solution must satisfy.

In addition to constraints, design criteria have a key role in engineering design. Criteria differ from constraints in that they are desired by the customer, but not required. Where constraints represent the "needs" of the customer, criteria represent the "wants". Pahl and Beitz describe criteria as *wishes*, which should be taken into considered whenever possible, but are secondary to constraints or *demands*. They are more qualitative, consisting of characteristics such as appearance, durability and ergonomics. Typically, design criteria are given a "weighting" based on their relative importance to the solution or the customer, so that the most important criteria can be given more focus throughout the design process. However, Pahl and Beitz contend that it is difficult to rank the criteria early in the design process and that new criteria are often discovered during the process (Pahl and Beitz, 1996). Furthermore, they explain that experience has shown the relative importance of criteria changes during the design process. Thus, design criteria are perhaps most useful when evaluating two or more design solutions that satisfy the constraints in order to determine which is the best solution or the most desirable to the customer.

In the beginning stage of the engineering design process, the design problem is formulated as a collection of requirements is developed. This set of requirements represents necessary aspects and functions of the design which are used as inputs and checks for the later design stages. The requirements phase of the design process can be broken down into elicitation, analysis, specification, and verification (Wiegers, 2003). Requirements elicitation is the process of gathering the requirements of all parties involved, from the client to the end user. Once gathered, requirements are analyzed for consistency and to ensure the collection is comprehensive. Then they are documented or modeled. Ultimately, they are verified by determining if they are satisfied by the design solution. Typically, requirements are established early in the design process, but are actually related throughout. A generally accepted design method is that of Pahl and Beitz, shown in Figure 3.1. As indicated by the areas highlighted in red, this method shows the requirements are generated early in the design process during the "Planning and clarifying the task" phase and are adapted throughout the design process.

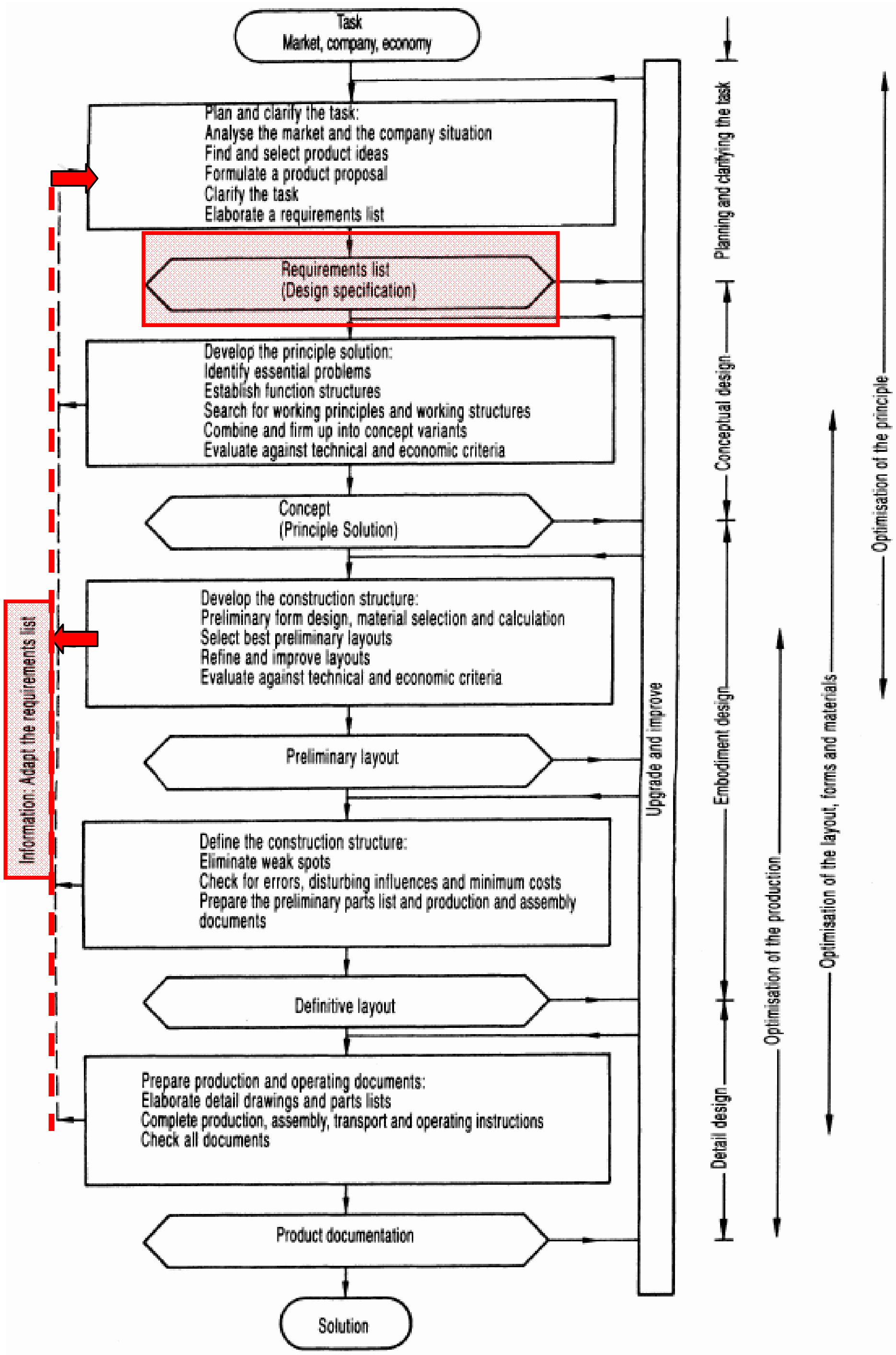


Figure 3.1 - Engineering Design Process (Pahl and Beitz, 1996)

Role of Requirements in the Design Process

The first step in the design process is to establish the requirements that will enable the design solution to satisfy a given set of needs. These needs can come from a variety of different sources. Most prominent are those established by company management and other high-level personnel. In some cases, these may be the sole requirements of a design. However, a designer should seek to elicit requirements from other people directly related to or affected by the eventual product. This can include component manufacturers, end users, and everyone in between. The design can only be fully defined once the needs of all parties involved are identified and related requirements are established. These requirements are then revisited and even revised throughout the design process, but the issues of when, how, and why are often unclear.

The design process begins with the identification of a societal need (Suh, 1990). Design objectives are then defined in terms of functional requirements (FRs) for which physical representations, described in terms of design parameters (DPs), are established. These functional requirements are established to satisfy the given set of needs and serve to define the design problem. The design process involves linking these functional requirements to the design parameters at each hierarchical level, which implies there is a hierarchy of requirements. When a design is created that does not fully satisfy the functional requirements, the designer must either develop a new design or change the functional requirements to more accurately reflect the societal need. In this way, it is an iterative process in which the designer has the ability to modify or change requirements throughout. In fact, Suh goes on to explain that one of the major problems in design is that designers “do not recognize the probable need to reiterate the establishment of functional requirements until a satisfactory design results.” (Suh, 1990). Thus, not only does a designer have the ability to evolve requirements, it is expected. Often the design resulting from a new set of functional requirements will be completely different from previous design solutions. Suh continues, stating that one mistake designers make is trying to revise or alter an existing solution to meet a new set of functional requirements as opposed to developing a totally new solution.

Functional requirements and design parameters have hierarchies and can be decomposed. However, FRs and DPs are interlinked such that a functional requirement cannot be decomposed to the next level without first developing a physical solution. Thus, the decomposition can only be accomplished by moving back and forth from the functional domain to the physical domain, as depicted in Figure 3.2. The designer must make sure a solution satisfies a given level FR with all the corresponding DPs before the FR can be decomposed to the next level of the hierarchy. The process stops when all FRs can be satisfied without further decomposition.

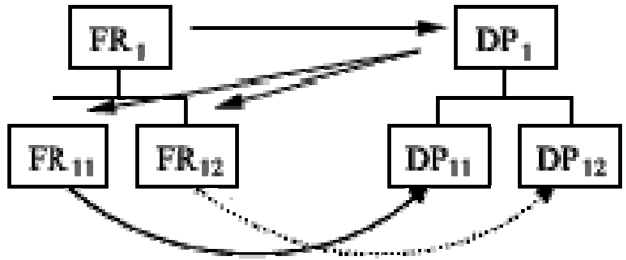


Figure 3.2 - Decomposing FRs and DPs (Suh, 2001)

The ability to decompose the FRs and DPs means a designer can manage the complexity of the design problem by focusing on a limited number of FRs at a time. Suh explains that a good designer has the ability to determine the most important FRs at each hierarchical level by disregarding less important factors (Suh, 1990). If the designer tried to consider all FRs at once, then the design process would become too complex to manage. This is in conflict with the strict idea of treating requirements as constraints. Thus, Suh looks at FRs as a combination of constraints and criteria which may be prioritized.

Hazelrigg argues that constraints are merely design decisions that have been made by high-level personnel or at a high level of design abstraction (Hazelrigg, 1996). These requirements are treated by the designer as immovable and thus limit creative freedom. As a result, a designer is forced to consider solutions that might have significant penalties, even though they may be unbeknownst to him. Thus, it is the responsibility of the designer to ask the question, "What are the consequences of a given requirement?" If the consequences are detrimental, then it serves to reason that a designer could theoretically eliminate or change a given requirement due to its origin as an earlier design decision.

Pahl and Beitz contend that it is possible to change or add requirements during the design process (Pahl and Beitz, 1996). They state that it is extremely important to document the source of requirements so that, if necessary, a designer can go back to the person who established a requirement and question the reasoning behind it. The most common reason for this is a design development that renders a requirement unnecessary or inaccurate. Often, the need to change or add a requirement is the result of an improved understanding of the various possible design solutions. Also, a change in emphasis of certain design aspects, such as from a client, could result in the need to revise the requirements. According to Pahl and Beitz, the head designer is responsible for conducting these enquiries, updating the requirements list, and making sure that all parties involved are informed.

Pahl and Beitz, Hazelrigg, and Suh all argue that a designer should continually question the need for each of the requirements and refine them as the product evolves. This is notable in that each author has approached design from a fundamentally different perspective, yet come to the same conclusion. When we look at the ideas described by these three, we can draw the conclusion that requirements can be decomposed, questioned, modified, and even changed completely. Ultimately, we see that requirements are design decisions made at the highest level. Thus, by decomposing the requirements, one can work backwards to uncover the original design decisions. If successful in deciphering the original design decisions, then it is reasonable that those decisions could be questioned and potentially altered.

Requirements Modeling Methods

A literature review found several methods for eliciting, defining, and modeling requirements. These methods come primarily from mechanical engineering and systems engineering disciplines. However, the methods vary in the way they classify or categorize requirements and in their ability to verify whether or not they have been met. Several of them do not differentiate between constraints and criteria, simply treating each as a requirement. This section will address the following methods: Requirements List (Pahl and Beitz, 1996), Product Design Specification (PDS) (Pugh, 1999), Systems Modeling (Hazelrigg 1996), Objective Tree (Pahl and Beitz, 1996), requirements in relation to product life cycle (Fu, 2003), and Quality Function Deployment (QFD) (Akao, 1994).

Requirements List

Perhaps the most basic form of gathering and modeling requirements is the generation of a Requirements List. In this method, each requirement generated by the designers or customers is documented and stored in a master list, which can be referenced for compliance throughout the design process. According to Pahl and Beitz (Pahl and Beitz, 1996), the requirements are separated into two categories, demands and wishes. They define demands as requirements that must be met and wishes as requirements that should be considered whenever possible, typically weighted in terms of importance. All of these requirements are included in the requirements list, which serves as an up-to-date working document that should be continuously reviewed. While Pahl and Beitz offer a recommended layout for a requirements list, shown in Figure 3.3, there are no formal guidelines for creating the list or for reviewing and verifying the requirements. Furthermore, the method does not make a clear distinction between detailed or sub-requirements and the related high-level requirement. The method does, however, successfully define the design project and provide a way to review and track requirements throughout the design process.

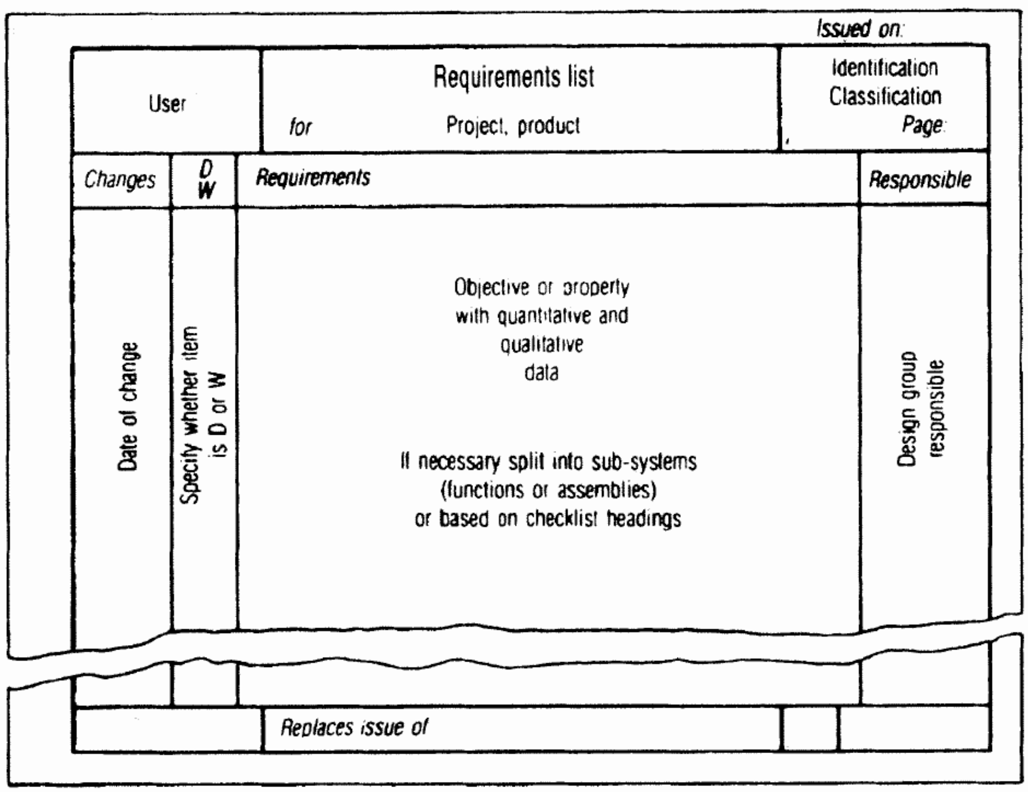


Figure 3.3 - Sample Requirements List Layout (Pahl and Beitz, 1996)

Product Design Specification (PDS)

The PDS method (Pugh, 1999) takes requirements modeling one step further, offering the ability to record and track requirements. It acts as a sort of living document that evolves throughout the design process, ultimately resulting in the final design requirements. This method incorporates requirements for both the primary design and benchmark designs, such as those of a competitor. The document includes requirements in categories such as environment, ergonomics, performance, safety and maintenance. However, these requirements are not clearly divided into constraints or criteria. Similar to a Requirements List, sub-requirements are not specifically linked to their corresponding high-level requirement and there is no capability for verifying that requirements are satisfied.

Systems Modeling

In the Systems Modeling approach presented by Hazelrigg, the objective is to obtain better overall design solutions by minimizing the need for constraints through the use of a system model that can accommodate increased complexity (Hazelrigg 1996). This method starts with a simple model of the entire system, broken down by subsystems. Each subsystem model is refined by incorporating increasing amounts of detail in order to design the individual system components. Therefore, a design solution can be obtained by resolving the overall system model at the level of detail in the subsystem models. The finer the level of detail of the subsystem models, the finer the detail of the overall design solution. While this method is effective at modeling high-system complexity, it does not differentiate between constraints and criteria or offer a process for verifying requirements.

Objective Tree

Objective trees are used to model the hierarchical nature of the requirements or objectives of a design problem. Used primarily in the early stages of design, this method helps to define the design problem and should be revisited during the design process to ensure that the design team is on task (Pahl and Beitz, 1996). An objective tree starts with the primary objective or goal of the design product based upon the problem definition. This objective is then decomposed into secondary requirements/objectives, from which further decomposition occurs at finer and finer levels of detail. An example objective tree for a burrito folding device is shown in Figure 3.4.

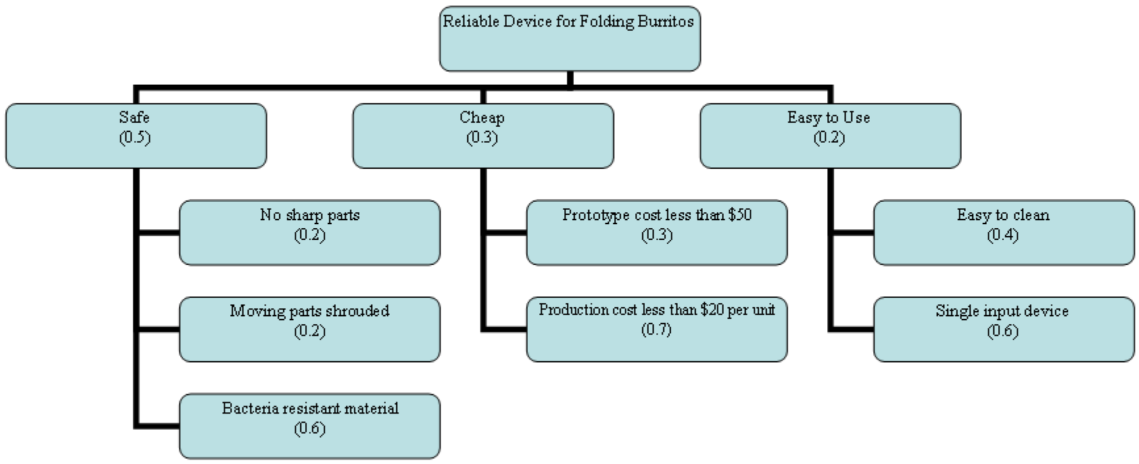


Figure 3.4 - Burrito Folder Objective Tree

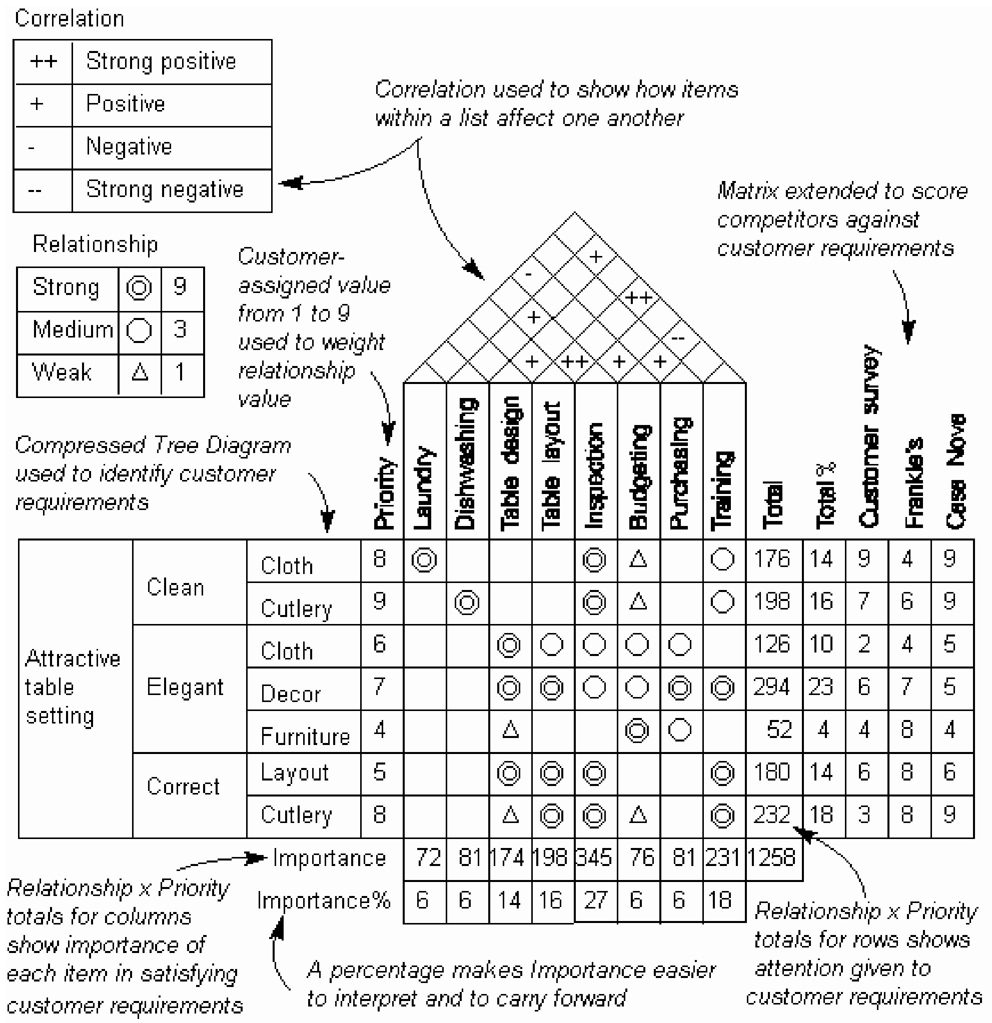
To illustrate the relative importance of each of the sub-objectives, weights can be assigned to the branches. These weights can then be used to calculate the final relative weights for the objectives at the leaves, which aid the designer in determining where to prioritize effort in the design process. The hierarchical nature of this method makes it effective at managing high levels of complexity, yet the method does not differentiate between constraints and criteria or offer a process for verifying requirements.

Requirements in Relation to Product Life Cycle

Another method, by Fu et al. (Fu, 2003), looks at requirements in relation to the product life cycle. In this method, requirements are categorized as Voice of the Customer (VOC), market requirements, statutory requirements, corporate requirements, and realization requirements. Unlike a Requirements List and PDS, this method supports requirement verification, which is carried out as the final step in the product development life cycle. While this is an improvement over other requirements modeling methods, it does not facilitate requirements verification in the early design phases. Similar to the previous methods, this approach does not distinguish between constraints and criteria.

Quality Function Deployment (QFD)

QFD is a method that helps to transform VOC requirements into realizable engineering characteristics. These characteristics are sorted and numerically prioritized. Thus, it very important to thoroughly understand the customers, how they are using existing products, and how they plan to use the new product in order to determine which "voices" are most important (Anderson, 1997). Cross contends that the person who buys the product is the most important and his/her "voice" must be given priority (Cross, 1994). Ultimately, the engineering characteristics are compared to customer quality demands in order to determine correlations and relative importance. A sample QFD matrix for the design of an attractive table setting versus the effort required in restaurant procedures is shown in Figure 3.5 and offers brief explanations for each section of the matrix.



Customer requirements for table-setting versus effort in restaurant procedures

Figure 3.5 - Table Setting QFD Matrix[7]

QFD was originally developed in Japan by Yoji Akao and is perhaps described best by Mr. Akao himself as a "method to transform user demands into design quality, to deploy the functions forming quality, and to deploy methods for achieving the design quality into subsystems and component parts, and ultimately to specific elements of the manufacturing process." (Akao, 1994). QFD can be used to review and update engineering characteristics as needed throughout the design process so that changes do not occur without the knowledge of the design team, which could lead to problems such as a sub-par product or a failure to meet deadlines (Ullman, 1997). Similar to QFD, the MOOSE method advocated by Gershenson, et al. (Gershenson, 1999) is to some extent clearer and more encompassing. This method expounds on QFD by using a taxonomy to classify customer requirements as either manufacturing, marketing, service, or financial. However, like the PDS method, MOOSE and QFD do not make a distinction between constraints and criteria nor do they provide correlations to testing in order to verify requirements are satisfied.

Requirements Modeling Methods Summary

The requirements modeling methods review uncovered a multitude of different approaches. The requirements phases and the main characteristics of each method are summarized in Table 3.1. Specifically, the phases are elicitation, analysis, specification, and verification. The characteristics are differentiating between constraints and criteria, hierarchy, collaborative, review/question requirements, and revise requirements.

[7] http://syque.com/quality_tools/toolbook/Matrix/vary.htm accessed November 17, 2009

Table 3.1 - Requirements Modeling Methods Summary

	Requirements List (Pahl & Beitz)	PDS (Pugh)	Systems Modeling (Hazelrigg)	Objective Tree (Pahl & Beitz)	Product Life Cycle (Fu et. al)	QFD (Akao)	FR - DP Mapping (Suh) *Note: not presented as a formal method
Phase:							
Elicitation	X	X	X	X	X	X	X
Analysis			X	X	X	X	X
Specification	X	X	X	X	X	X	X
Verification					X		X
Characteristics:							
Differentiate between Constraints & Criteria	X						
Hierarchy			X	X			X
Collaborative	X				X	X	
Review/Question Requirements	X	X					X
Revise Requirements	X	X					X

Comparing the capabilities of each of the various requirements modeling methods reveals that there is no single comprehensive method. While some methods are more encompassing than others, none address all the requirements phases and characteristics. Therefore, a designer must select and adapt various aspects of two or more different methods in order to create one comprehensive approach. Undoubtedly, this can be difficult and time consuming, as well as problem specific. A customized method that works for one problem may not work for others. Thus, there exists a need to develop a comprehensive requirements modeling method that can be applied to a wide range of design problems. This thesis will focus on three capabilities generally lacking from current requirements modeling methods: requirements verification, review/question requirements, and revise requirements. Through the use of a large industry design project case study, this thesis will show that requirements can be verified both by testing and by identifying customer needs. Thereby enabling the designer to challenge and ultimately revise those requirements.

CHAPTER 4

EAI REQUIREMENTS

At the beginning of the project, the initial requirements were given by the customer, Environmental America. These requirements are based on the customers understanding of the market and their experiences constructing several prototypes and conducting tests. Additionally, further requirements were established by identifying external customers, such as the Federal Motor Car Safety Administration (FMCSA) and the Occupational Health and Safety Administration (OSHA). Individual requirements were then established for each of these customers. Once all requirements were established, it was necessary to determine the best way to present them and track any changes.

After several discussions with the customer, it was concluded that a requirements list, shown in Table 4.1, would be the best way of displaying, organizing, and revising these requirements. This was chosen over other more powerful and complicated tools, such as Quality Function Deployment (QFD) because it provided the best means for effective communication between the design team and the customer. More complex requirements modeling tools would have overwhelmed the customer, making it difficult to communicate and potentially slowing the design process.

Table 4.1 – Initial Customer Requirements

No.	Description	Target Value	Target Unit	Justification/ Origination	Date Defined	Date Revised
1.	Must process 350 households per day	350	H/D	EAI	9-6-05	
2.	Must provide storage for 350 households per day	350	H/D	EAI	9-6-05	
2.1	Must Separately store different categories of recyclables, plus trash	11	Recyclables	EAI	9-6-05	
2.2	Must store trash		ft^3	EAI	9-6-05	
2.3	Must store newspaper		ft^3	EAI	9-6-05	
2.4	Must store cardboard		ft^3	EAI	9-6-05	
2.5	Must store chipboard		ft^3	EAI	9-6-05	
2.6	Must store PET		ft^3	EAI	9-6-05	
2.7	Must store clear HDPE plastic		ft^3	EAI	9-6-05	
2.8	Must store white HDPE plastic		ft^3	EAI	9-6-05	
2.9	Must store clear glass		ft^3	EAI	9-6-05	
2.10	Must store green glass		ft^3	EAI	9-6-05	
2.11	Must store brown glass		ft^3	EAI	9-6-05	
2.12	Must store aluminum cans		ft^3	EAI	9-6-05	
2.13	Must store steel cans		ft^3	EAI	9-6-05	
3.	Must shred plastics before storage			EAI	9-6-05	
3.1	Must shred PET			EAI	9-6-05	
3.2	Must shred clear HDPE plastic			EAI	9-6-05	
3.3	Must shred white HDPE plastic			EAI	9-6-05	
4.	Must crush glass before storage			EAI	9-6-05	
4.1	Must crush clear glass			EAI	9-6-05	
4.2	Must crush green glass			EAI	9-6-05	
4.3	Must crush brown glass			EAI	9-6-05	
5.	Must crush aluminum cans before storage			EAI	9-6-05	
6.	Must crush steel cans before storage			EAI	9-6-05	
7.	Must bale paper products			EAI	9-6-05	
7.1	Must bale cardboard			EAI	9-6-05	
7.2	Must bale chipboard			EAI	9-6-05	
7.3	Must bale newspaper			EAI	9-6-05	
8.	Recyclables must be removed by industrial vacuum			EAI	9-6-05	

No.	Description	Target Value	Target Unit	Justification/ Origination	Date Defined	Date Revised
8.1	Fluid must be removed from recyclables before vacuuming			EAI	9-6-05	
9.	Maximum unloaded vehicle weight	50,000	Lbs	EAI considerations / FMCSA – Sec. 658.17[1]	9-6-05	
10.	Maximum unloaded vehicle height	161	In	EAI	9-6-05	
11.	Maximum vehicle width	102	In	FMCSA – Sec. 658.15	9-6-05	
12.	Must comply with all commercially operated vehicle rules and regulations			Federal and State Laws	9-6-05	
12.1	Must satisfy rear outboard seating position regulations			FMCSA – S4.2, S4.3, S7.1[2]	9-6-05	
12.2	Must meet operator work regulations			OSHA Regulations	9-6-05	
12.3	Must not exceed interior sound level at driver's seating position	90	Db	FMCSA – Sec. 393.94	9-6-05	
12.4	Must not exceed maximum permissible sound level readings	See Figure 4.1	Db	FMCSA – Sec. 325. **7**	9-6-05	
12.5	Must satisfy truck access requirements			FMCSA – Sec. 399.207	9-6-05	
13.	Requires standardized trash can for all households serviced				9-6-05	

Consider maximum allowable gross vehicle weight of prominent South Carolina bridges
[2] Regulations for gross vehicle weight of 10,000 pounds or less

The allowable noise levels shown in Figure 4.1 are an example of the external requirements established. This requirement comes from a government entity and represents the expansion of the requirements list from just those of the primary customer. When dealing with large entities like the FMCSA and OSHA, it is hard to capture their vast number of rules and regulations. Therefore, it is common practice to construct a complete working prototype and meet with company representatives to conduct inspections. This is the most practical way to identify all of the requirements for large customers.

Sec. 325. 7 - Allowable noise levels.
Motor vehicle noise emissions, when measured according to the rules of this part, shall not exceed the values specified in Table 1.
Table 1--Maximum Permissible Sound Level Readings (Decibel (A)) \1, 2\

If the distance between the microphone location point and the microphone target point is--	Highway operation test				Stationary tests	
	Soft site		Hard Site		Soft site	Hard Site
	35 mi/h or less	Above 35 mi/h	35 mi/h or less	Above 35 mi/h		
31 ft (9.5m) or more but less than 35 ft (10.7m)............................	87	91	89	93	89	91
35 ft (10.7m) or more but less than 39 ft (11.9m)............................	86	90	88	92	88	90
39 ft (11.9m) or more but less than 43 ft (13.1m)............................	85	89	87	91	87	89
43 ft (13.1m) or more but less than 48 ft (14.6m)............................	84	88	86	90	86	88
48 ft (14.6m) or more but less than 58 ft (17.1m)............................	83	87	85	89	85	87
58 ft (17.1m) or more but less than 70 ft (21.3m)............................	82	86	84	88	84	86
70 ft (21.3m) or more but less than 83 ft (25.3m)............................	81	85	83	87	83	85

\1\ The speeds shown refer to measurements taken at sites having speed limits as indicated. These speed limits do not necessarily have to be posted.
\2\ This table is based on motor carrier noise emission requirements specified in 40 CFR 202.20 and 40 CFR 202.21.
[40 FR 42437, Sept. 12, 1975, as amended at 54 FR 50385, Dec. 6, 1989]

Figure 4.1 - Federal Motor Car Safety Administration - Allowable Noise Levels

Although the design team attempted to define as many external customers and requirements as possible, it is not uncommon for more to be discovered and added throughout the design process. Thus, the requirements list is a living document that is revised throughout the design process.

Requirements Validation

After establishing the initial requirements and the various 350 household recyclables volumes, guidelines for validating the requirements were established. While some of these requirements could be evaluated at the conceptual level, many of them required real-world testing. Therefore, some requirements could not be evaluated until a complete working prototype was constructed, so engineering judgment was necessary in some cases to determine if a design would meet a given requirement. The general validation guidelines for each given requirement are briefly explained below:

1. Must process 350 households per day – Test runs on actual or simulated collection days can confirm the efficiency and effectiveness of the truck and its systems.

2. Must provide adequate storage for 350 households per day – Conduct tests using the prototype vehicle to determine actual material processed volumes vs. unprocessed volumes and compare to the established targets and vehicle storage space.

2.1 Must keep MSW and different recyclables sequestered – The fundamental design of the vehicle, coupled with visual validation during testing, can confirm materials are stored separately.

2.2 – 2.13 Must store MSW and individual recyclables – Vehicle layout and visual validation of storage areas will be adequate.

3. – 7 Must process recyclables – The ability of the individual processing systems to perform assigned tasks and meet required material capacities will be evaluated in testing.

8. Recyclables must be removed by industrial vacuum – Processed material component weights will be used to gauge their ability to be removed by the vacuum system and testing will be conducted for final validation.

8.1 Fluids must be removed before vacuuming – Test runs of the vacuum system on actual or simulated collection days will be observed to confirm that ample fluid is vacated from the bins so as not to adversely effect operation.

9. Maximum unloaded vehicle weight – The weight will be estimated using solid modeling during the design process and verified by a certified South Carolina Department of Transportation truck scale.

10. Maximum unloaded vehicle height – The truck height will be measured according to the guidelines set forth by the FMCSA.

11. Maximum vehicle width – As above, the width will be measured according to the guidelines set forth by the FMCSA.

12 – 12.5 Compliance with local, state and federal regulations – In addition to regulations and testing procedures issued by the FMCSA, the team will be in contact with various government agencies to ensure proper design rules are followed. An inspection of the final prototype/product will serve as the final validation.

13. Requires a standard trashcan – This will most likely be chosen by the customer based on price, availability, aesthetics, and OEM specifications for the automated loader. Testing will verify proper operation.

EAI Design Criteria

In addition to the requirements, a list of design criteria were also established, which can be found in Table 4.2. While the requirements are evaluated on a "pass" or "fail" basis, the design criteria are not absolutes. They are evaluated based on how well one solution satisfies them relative to other solutions. The criteria are secondary to the requirements and the majority of them were set by the design group after meeting with the customer and dissecting the design problem. Where the requirements represent the “needs” of the customer, the criteria represent the “wants” of both the customer and design team with the shared goal of maximizing vehicle effectiveness and efficiency.

Table 4.2 – Initial Design Criteria

No.	Wt.	Description	Target Value	Target Unit	Justification/Origination	Date Defined	Date Revised
1.	9	Should minimize time required to gather, sort, and process recyclables	≤ 80	Seconds/ household	Outperform necessary 350 house mark	9-6-05	
2	3	Should minimize the number of crew operators	2	Men		9-6-05	
3.		Should minimize operator work				9-6-05	
3.1	3	Should minimize the number of steps taken in a day		Steps		9-6-05	
3.2	3	Should minimize the amount of weight lifted in a day		Lbs		9-6-05	
3.3	3	Should minimize the distance load is carried		Ft		9-6-05	
3.4	1	Should minimize ergonomic reach				9-6-05	
3.5	1	Should simplify user controls for various systems				9-6-05	
4.	3	Should reduce the total number of systems		Systems		9-6-05	
5.	3	Should minimize the number of power sources	1	System		9-6-05	
6.	9	Should minimize total vehicle cost	TBD	Dollars		9-6-05	
7.		Should minimize the size and weight of the vehicle			Increase maneuverability, fuel mileage, and outreach	9-6-05	
7.1	3	Should minimize unloaded vehicle weight	TBD	Lbs		9-6-05	
7.2	1	Should minimize vehicle height	144	In	EAI	9-6-05	
7.3	1	Should minimize vehicle width	96	In	EAI	9-6-05	
8.	3	Should minimize vehicle noise level		Db	Home Owner Associations	9-6-05	

No.	Wt.	Description	Target Value	Target Unit	Justification/Origination	Date Defined	Date Revised
9.	3	Should utilize commercially available equipment when possible			Decreased equipment cost. Parts availability aids in minimizing maintenance time and cost.	9-6-05	
10.		Should be simple and economical to maintain				9-6-05	
10.1	3	Should minimize frequency of maintenance		Hrs/miles	Reduces downtime, which increases profit	9-6-05	
10.2	3	Should minimize maintenance time			Reduces downtime, which increases profit	9-6-05	
10.2.1	3	Should utilize one system (English or Metric)			Aids in reducing maintenance time	9-6-05	
10.2.2		Should be easy to service systems			Aids in reducing maintenance time	9-6-05	
10.2.2.1	1	Should be easy to access systems				9-6-05	
10.2.2.2	1	Should be easy to uninstall components				9-6-05	
10.2.2.3	1	Should be easy to repair/replace components				9-6-05	
10.2.2.4	1	Should be easy to reinstall components				9-6-05	
10.3	9	Should minimize maintenance cost				9-6-05	
11.	3	Should be aesthetically pleasing			More appealing to customers as well as homeowners. The truck will often be in the neighborhoods it services.	9-6-05	
12.	9	Should be highly modular			Marked differences between recyclable characteristics in different neighborhoods	9-6-05	

NOTE: Weights are given on a scale of {1, 3, 9}

In order to focus design efforts on the most important criteria, a 1, 3, 9 scale was used to weight them from lowest to highest in terms of importance to the customer and design team. In this case, the least important criteria were given a score of one, moderately important criteria a three, and the most important received a score of nine. The score for each criterion was initially selected by the design team and then discussed with the customer at subsequent meetings. For the most part, the final criteria weighting were agreed upon by the customer and designers, with the customer having executive power when no clear consensus could be reached.

Criteria Evaluation

Although Environmental America is the primary customer, other customers and end-users had to be considered when determining the criteria and methods of evaluation. Most of the design criteria tend to focus on vehicle cost, efficiency, and service. Thus, some of the customers and users that had to be considered were the operators, technicians, and distributors or salespersons. The goal was to evaluate the criteria in a manner that would address their needs. Many criteria, such as simplistic maintenance, could not be accurately evaluated until construction of the prototype. However, some criteria were more fundamental in nature and could be carefully considered and evaluated throughout the design process.

1. <u>Minimize time required to gather, sort, and process recyclables</u> – Measured in time, this criterion will be a reliable way to measure short-term or small-scale efficiency. It may be best measured subsystem by subsystem.

2. <u>Minimize the number of crew operators</u> – With fewer operators, overhead can be cut, maximizing profits. The current crew goal is two: one driver and one collector/sorter.

3. – 3.5 <u>Minimize operator work</u> – By reducing the number of steps taken, weight lifted, and distance the load is carried, the operator will expend less energy during a shift.

4. Reduce number of subsystems – The count of subsystems is a straightforward way to verify the simplicity of the vehicle.

5. Minimize number of power sources – Power generated by only one source (i.e. electrical or hydraulic) could simplify and lighten systems, making the truck more efficient overall.

6. Minimize total vehicle cost – Cost will be compared to other vehicles currently operating in the target market, but must ultimately be financially viable to the client.

7. – 7.3 Minimize vehicle size and weight – Reducing the overall size of the vehicle (length, width, height, and weight) beyond what is required by law.

8. Minimize noise level – The noise level measured in decibels will be decreased beyond the legal restrictions.

9. Utilize commercially available equipment when possible – This can be confirmed by the use of "bolt-on" or "off-the-shelf" components.

10. – 10.3 Economic and simplistic maintenance – This can be verified during development, as systems will need to be installed and serviced on the prototype.

11. Aesthetics – This can only be verified as the prototype is developed and subjective opinion can be gauged.

12. Modularity – This will be verified on test runs in actual communities. The adaptability of the truck will be evaluated during operation in a variety of neighborhoods.

The requirements and design criteria developed formed the basis for generating and evaluating design concepts. They served as the guiding conceptual design principles, which were refined and expanded throughout the design process. Additionally, they provided a means for comparing different design concepts. After establishing the requirements and design criteria, the project progressed to the concept generation phase.

CHAPTER 5

EXPLORED DESIGN CONFIGURATIONS

The initial customer requirements and design criteria were used to develop several design concepts that explored many different vehicle configurations and processing systems. The concepts were generated using several different methods, including brainstorming, collaborative sketching, and even drawing an idea on a napkin at lunch. They were then presented to the customer and the two most promising concepts, according to the opinion of both the customer and the design team, were chosen for further development and evaluation. These concepts were actually very different, representing two unique solutions to the design problem. During these discussions, it was also determined that target values for the MSW and recycling volumes of 350 households needed to be established in order to accurately develop and compare the concepts.

Unprocessed Volume Comparison for 350 Households

In order to determine target volumes for MSW and recycling, the team first examined data collected by EAI during testing with the prototype vehicle. Before joining with Clemson University, EAI had conducted a recycling collection volume test in which they collected the trash and recycling from 125 houses in Greenwood, South Carolina, where the company is headquartered. The results of this “125 House Blue Box Test” are shown in Figure 5.1. The customer’s goal was to determine volume targets for the various recyclables collected. According to them, the test volumes represent roughly a 70% recycling rate, where items found in the homeowner’s trash that were not recycled were removed and added to the recycling bins.

2-11-99

PROTOTYPE IV HOUSEHOLD PICKUP PROJECTIONS BASED ON THE 125 BLUE BOX TEST
INTERIOR CONTAINERS 8 CATEGORIES 5 CRUSHED & 3 SHREDDERED IN POUNDS

			----------------QTY'S--------------------------			
	POUNDS	LBS/PU	400	500	600	700
(PET) SOFT DRINK	29.00	.232	92.80	116.00	139.20	162.40
HDPE MILK JUGS	15.50	.124	49.60	62.00	74.40	86.80
HDPE MIXED	30.00	.240	96.00	120.00	144.00	168.00
STEEL CANS	33.00	.264	105.60	132.00	158.40	184.80
ALUM CANS	12.00	.096	38.40	48.00	57.60	67.20
GLASS CLEAR	88.00	.704	281.60	352.00	422.40	492.80
GLASS BROWN	8.13	.065	26.00	32.50	39.00	45.50
GLASS GREEN	4.25	.034	13.60	17.00	20.40	23.80
TOTALS POUNDS			703.60	879.50	1055.40	1231.30

2-11-99

PROTOTYPE IV HOUSEHOLD PICKUP PROJECTIONS BASED ON THE 125 BLUE BOX TEST

			-------------PICKUP QTY'S-------------------------------			
			400	500	600	700
			--------------------POUNDS------------------------------			
CARDBOARD	100.00	0 .80	320.00	400.00	480.00	560.00
BALES PER OUR SYSTEM			0.90	1.12	1.35	1.57
CHIPBOARD	140.00	1.12	448.00	560.00	672.00	784.00
BALES PER OUR SYSTEM			1.12	1.40	1.68	1.96
NEWSPAPER	541.00	4.33	1731.20	2164.00	2596.80	3029.60
BALES PER OUR SYSETM			2.89	3.61	4.33	5.05
MAGAZINES	80.00	0.64	256.00	320.00	384.00	448.00
BALES PER OUR SYSTEM			0 .38	0 .47	0.56	0.66
TOTALS			2755.20	3444.00	4132.80	4821.60

Figure 5.1 - EAI 125 House Blue Box Test Results

The results from the EAI study were reported in units of weight, which needed to be converted to volumes in order to be more useful from a design standpoint. Thus, Standard Volume-to-Weight Conversion Factors from the United States Environmental Protection Agency (EPA, 1997), found in Appendix D, were used to determine the volumes. When a range of values was given, the average value was used for calculations. Based on the EAI test results and the EPA established conversion factors, the 350 household volumes for the various recyclables were calculated as shown in Table 5.1.

Table 5.1 - EAI 350 Household Volumes

Material	EAI-125 House Weight (lbs.)	Weight to Volume Conversion Factor (ft3/lb)	EAI-125 House Unprocessed Volume (ft3)	EAI-350 House Unprocessed Volume (ft3)
Newspaper	541.0	0.06	33.8	94.6
Cardboard/Chipboard	240.0	0.16	37.8	105.7
Magazines	80.0	0.04	3.3	9.2
Clear Glass	88.0	0.05	4.0	11.1
Brown Glass	8.1	0.05	0.4	1.0
Green Glass	4.3	0.05	0.2	0.5
Steel Cans	33.0	0.18	5.9	16.6
Aluminum Cans	12.0	0.43	5.2	14.5
PET Soft Drink	29.0	0.77	22.4	62.6
HDPE Milk Jugs	15.5	1.13	17.4	48.8
HDPE Mixed	30.0	0.54	16.2	45.4

In an effort to validate these targets, a high level survey was conducted in which various other recycling volume data was collected and compared to the EAI values, see Table 5.2. The recycling data consisted of overall United States generation data, data from several different states, and from the local South Carolina County, Pickens County. Volumes for 350 households were then determined based on the published recycling or generation rates and 2000 United States Census Bureau[8] data for population and household size. Since each state and locality reported their numbers differently, some adjustments were made in order to more accurately compare the data.

In Table 5.2, columns labeled "Recycled" were calculated from the recycling data while those labeled "Generation" were calculated from studies conducted by the states of their respective MSW streams. The final 350 household results from the "Recycled" columns were then increased by 20% in order to provide a conservative estimate and to account for an expected increase of recycling due to the convenience of curbside pickup. It was also noted that Virginia and South Carolina report both paper and cardboard in the same category. For the purposes of this study they were divided using the national numbers to create percentages. Conversely, some states provided a detailed breakdown of recyclables. In this case, the specific categories were combined to fit what the design team thought would be considered recyclable paper, plastic and metal.

Table 5.2 - Unprocessed Volume for 350 Households

Volume (ft^3)	US Generation 1997 (Res)	WI Generation 2000 (Res & Com)	SC Recycled 2004 (Res)	IA Generation 1998 (Res & ICI)	MN Recycled 2002 (Res & ICI)	VA Recycled 2002 (Res & ICI)	Pickens County 2004 (Res & ICI)	350 Home EAI Study
Aluminum Cans	84.0	89.1	61.0	24.9	173.6	557.4	5.9	14.5
Cardboard	307.7	1117.7	92.1	633.1	759.8	526.5	161.1	105.7
Glass	48.3	53.9	4.4	14.6	17.5	18.9	7.6	12.6
Mixed Paper	114.3	425.5	34.2	157.3	188.8	195.7	45.9	103.8
Plastic	812.8	373.4	52.6	305.3	366.4	655.8	63.4	156.8
Steel Cans	54.3	62.3	394.6	194.1	233.0	361.7	5.4	16.6

In addition to residential volume, much of the data gathered included Industrial, Commercial, and Institutional (ICI) which is by far the biggest producer of waste

[8] http://www.census.gov/main/www/cen2000.html accessed October 20, 2005

(SWRC, 2005). Unfortunately, the ICI data was combined with residential and there was no way to accurately separate the two. There was also a large difference between values for different parts of the country, which could be attributed to many different factors such as the culture, amount of commercialization, and the recycling programs in place. The volumes from the EAI study were significantly larger than those of Pickens County, South Carolina, even though the county numbers included ICI recycling. This is likely the result of the 70% recycling rate EAI estimated for their test. However, the test values were significantly lower than the residential US generation in many cases, which could be consequential or simply the result of a difference in reporting method. Ultimately, EAI made an executive decision to utilize the volume targets extrapolated from their "125 House Blue Box Test" due to the inconsistency in the data gathered and the need to move the project forward. The company representatives were satisfied to use their numbers, stating that they were confident in the method used to obtain them and the ability of a truck designed with those targets to be effective in the market place. They also envision that the collection volumes of future vehicles will be able to be tailored to meet individual clients' needs.

Design Concepts

With the requirements, design criteria and volume targets fully defined, the two most promising design concepts were further developed and compared. These two concepts were selected by the client and design team after several concept review meetings. The designs represented two very different solutions to the problem, with each one serving a very specific purpose. Design 1, or the "Drop-frame Design" was an evolutionary solution that addressed many of the shortcomings and concerns of the current EAI prototype without any radical change to the overall design concept. While Design 2, the “Baler Design” was a completely outside-the-box approach to the problem that even though it did not meet some of the material processing requirements, the client and design team agreed that it warranted further development.

The first design concept, Design 1 – Drop-frame Design, utilized an assortment of shredders, crushers, and balers; similar to the EAI prototype vehicle, see Figure 5.2. However, the key difference was that the design utilized a drop-frame vehicle chassis, which has a section between the axles that is lower, typically by about 15 inches, than the rest of the frame rails. Research showed that the most notable manufacturers of large drop frame chassis for the refuse industry are Mack Trucks[9], Crane Carrier[10], and Peterbilt[11]. While these chassis are typically more expensive than their non-drop-frame counterparts, they offer design flexibility and improved vehicle ingress and egress.

[9] http://macktrucks.com/#/home accessed November 20, 2009
[10] http://cranecarrier.com/ accessed November 20, 2009
[11] http://www.peterbilt.com/index.aspx accessed November 20, 2009

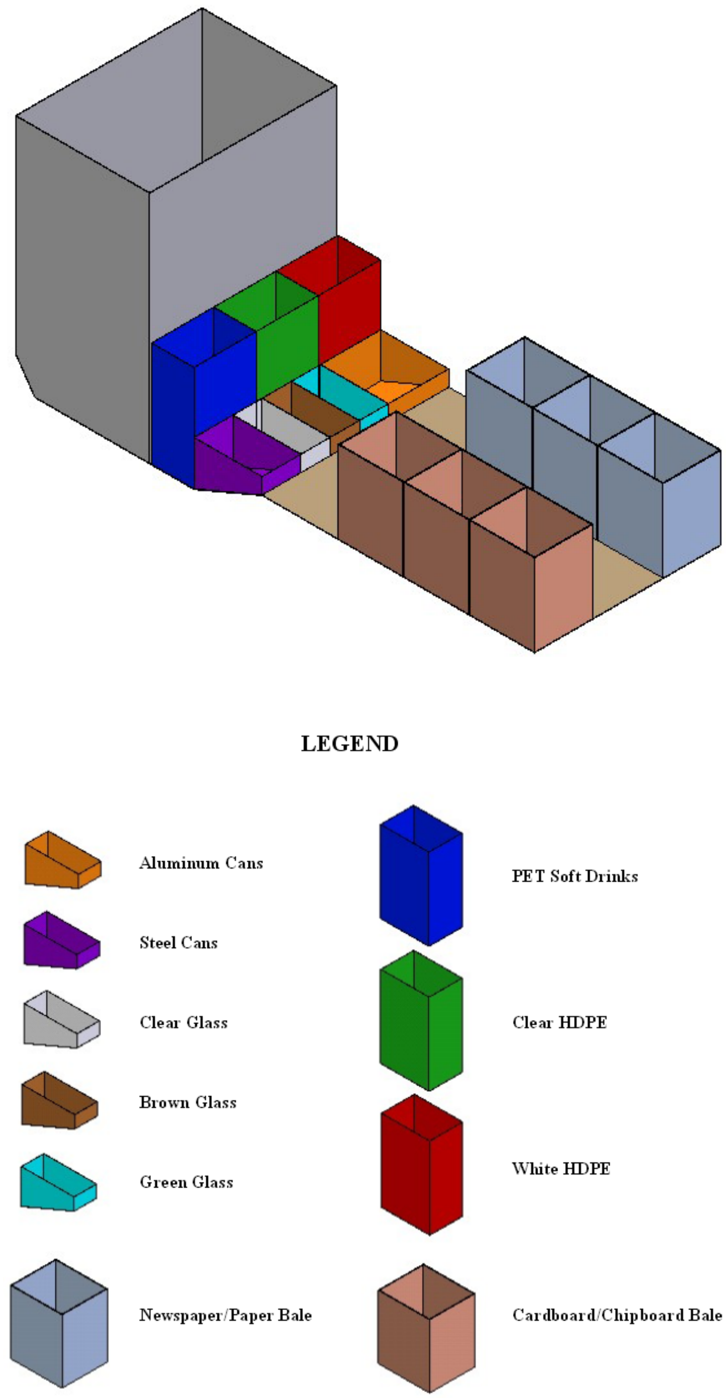


Figure 5.2 – Design 1 – Drop-frame Design

The use of the drop-frame chassis enabled the shredder and crusher bins (glass, plastic, aluminum, and steel) to be positioned below the operator floor, making it possible for the operator to directly feed the processing units by hand. This was a significant improvement over the slow and complicated device on the EAI prototype that drove the recyclables up to the top of the vehicle before unloading them into the processing units. The design team envisioned that the shredder and crusher units would be placed above their respective storage bins and would have tapered, gravity-fed, shoots above them that the operator would load. These shoots would have doors that automatically closed before the crushers and shredders were activated in order to ensure operator safety. Additionally, the multi-bin balers found on the EAI concept were turned ninety degrees and moved to the rear of the vehicle. This move created one work space where a single operator could load all categories of recyclables for processing. At the same time, it helped to reduce the overall width of the vehicle, which is critical for navigating narrow neighborhood streets. Thus, this design enabled the recyclable processing to be conducted by a single operator housed within the truck body.

The second design concept evaluated, Design 2 – Baler Design, used only vertical multi-bin balers and crushers, see Figure 5.3. The most important feature of this design was the processing of recyclables by one uniform method, baling. The only exception was the use of crushers for the glass containers, which the team envisioned would be small, off-the-shelf units due to the relatively low volumes of glass containers. With only two processing methods and the use of off-the-shelf items, the concept was significantly less complex than the current vehicle prototype. Furthermore, it offered great flexibility both in vehicle configuration and sub-system quantity and size.

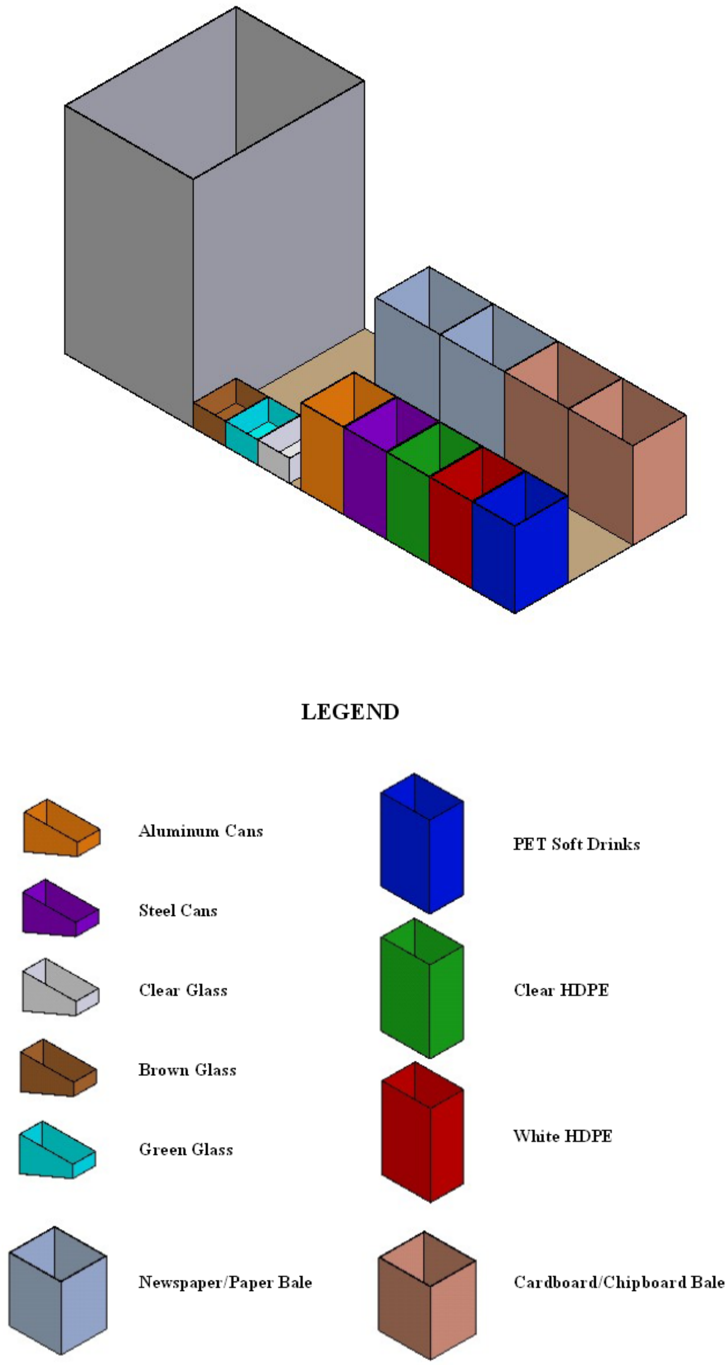


Figure 5.3 – Design 2 – Baler Design

The concept utilized a standard or non-drop-frame chassis to support the MSW and recyclable processing. Despite the use of a standard chassis, the recycled material bins could be sized to meet volume targets while still presenting easy operator loading due to the use of balers as the primary processing units. Additionally, the relatively small glass recyclable volumes made it possible to load the glass crushers from a standing position. The balers ran front to back, creating two separate multi-bin units that required just one traversing ram each. Also, the orientation of the balers ensured that a single operator could access all recyclable processing from within the vehicle. The design team envisioned that the baler doors would be located on the exterior of the vehicle in order to facilitate material off-loading.

Concept Evaluation

After defining the two design concepts to a sufficient level for evaluation, they were compared and assessed in a variety of different ways. First, it was determined if they satisfied the design requirements. From there, the designs were evaluated on how well they met some of the design criteria. In this case, the highest weighted and thus most important design criteria were given more consideration. The designs were compared to each other in order to determine where and why one design was better than the other. Ultimately, the team was able to determine how to proceed with the design development.

Requirement Filter

The first level of evaluation was to check that both designs satisfied the requirements. After examination, Design 1 successfully satisfied all the requirements, but Design 2 did not. Design 2 failed to fulfill the processing requirement of shredding and the related vacuum material removal requirement. This was foreseen by the design team and is a product of the designs use of only balers and crushers, the very simplicity that makes the design attractive. Traditionally, this design would have been thrown out as a requirement filter is usually “pass” or “fail”; and if a design fails just one requirement, it is rejected entirely. However, the simplicity of the design was so compelling that the team questioned the need to shred certain recyclables. After explaining the design to the client, the client agreed that the design should be further considered.

Comparisons

With client approval to continue evaluating the concepts, the next step was to evaluate the designs against the criteria and each other. The criteria focused on for comparison were those with a weighting of 3 or 9 on a 1, 3, 9 scale. This consisted of criteria such as minimizing operating time, total vehicle cost, and maintenance cost, as well as designing the vehicle to be highly module. The design aspects related to each criteria were compared to determine which design best satisfied the given criterion.

When comparing the designs, the main focus was vehicle complexity and flexibility. Specifically, the number of processing systems, types of power sources, vehicle chassis, and ability to reconfigure the vehicle. Design 1 utilized two power sources, electric and hydraulic, to operate three different processing systems (shredders, crushers, and balers). However, Design 2 utilized just one primary power source, hydraulic, and only two processing systems (crushers and balers). Furthermore, the Baler Design required only two hydraulic rams and hydraulic commercial glass crushing units for processing, while the Drop-frame Design required multiple shredders and crushers in addition to two hydraulic rams. The simplicity of the Baler Design and the extensive use of hydraulics increased the likelihood that the systems could be powered by a motor-driven hydraulic pump and an extra alternator for the control systems. This was contrary to the large, costly, and noisy generator required to operator the numerous systems in the EAI prototype and the Drop-frame Design. Additionally, the more simplistic Baler Design utilized a standard, widely available, vehicle chassis as opposed to the more unique and expensive drop-frame chassis.

Investigating vehicle operation and design flexibility revealed that Design 2 had several advantages over Design 1. First, the Baler Design used only two operators compared to the three operators required for Design 1. Second, it used a similar processing method for all recyclables. This should reduce the required personnel aptitude and lead to fewer operator errors. The combination of less personnel and decreased operator error should result in a shorter operating time and decreased operating cost. Finally, the use of single processing method for all recyclables increases the vehicles flexibility compared to the Drop-frame Design. Essentially, the type of recyclable material stored in each baler bin could be altered slightly without requiring the vehicle to be physically reconfigured. For example, if a given collection route produces more paper than cardboard; a paper storage bin could be eliminated and designated as cardboard storage. When more significant reconfigurations are needed, it is possible to alter the size or quantity of bins without increasing the number of systems.

Product development, manufacturing and maintenance were some of the other important design criteria that were considered. In terms of development, the Baler Design would have a shorter time to market due to the fewer number of systems and their relative simplicity. The simplicity of the baler system and the similarity of the lower number of components should reduce manufacturing and maintenance time as well as associated cost. Additionally, the use of a single hydraulic power system is more beneficial than the dual electric and hydraulic system of Design 1 in terms of development, manufacturing, and maintenance. Ultimately, the Baler Design is less complex, making it faster to develop and cheaper to manufacture and maintain than the Drop-frame Design.

Results

After comparing the two design concepts, the design team concluded that the Baler Design, Design 2, was the overall better solution despite the fact that it did not satisfy all the customer requirements. Fortunately, the client had given the team permission to further investigate the design and was intrigued by the findings of the comparison with the other design concept. In the traditional mind set where the customer is always right (C.-H. Chen et al., 2002; DuBrin, 2008), this solution would not have made it off the drawing board. However, based on the promising results of the comparison, the design team took the approach that the customer does not always know what the customer wants (Peterson, 2007; Roberts, 1989). Thus, the violated requirements were questioned and challenged.

CHAPTER 6

REQUIREMENTS CHALLENGED

In engineering design there exist situations in which a designer may find him or herself questioning customer requirements. These situations can occur at various stages of the design process and for several different reasons. For example, if the requirements are based on assumptions or information which is determined to be inaccurate or incomplete, then it is rational, and even necessary, to question those requirements. Also, it is possible for different customers to establish conflicting requirements, in which case the designer must determine how to reconcile them. Furthermore, requirements can be found to conflict with industry practices, violate regulations or design codes, and in some cases can even be unachievable.

Challenging requirements is not a simple process of properly applying design tools or rules. It is generally accepted that this process requires careful evaluation, practical experience, good communication, and sound engineering judgment. However, there are a few concepts that can help an engineer to challenge requirements. Based on this case study, three concepts for challenging requirements were identified. Those concepts are testing, defining more customers and refining their needs, and breaking down a requirement to its original design decision.

Conducting tests and gathering data can show the need to change or eliminate a requirement. While a requirement may overly narrow the design scope, or appear solution based, the designer must be able to offer proof of this finding. Test results can be used to demonstrate the inaccuracy of a requirement and the feasibility of an alternative solution. This can enable the designer to revise or replace requirements either by showing that a requirement is not possible or that a better solution exists. Additionally, testing generates tangible results which are critical in illustrating requirement shortcomings and convincing a client of the need for refinement. However, testing is only useful once a designer has identified an area requiring further investigation.

Defining more customers and refining their needs can reveal conflicting or obsolete requirements. As more customers are identified, the likelihood of uncovering a conflict increases. For example, in the case of the residential curbside collection vehicle, the customers may be initially established as the client (municipality that is purchasing the vehicle) and end users (personnel operating the vehicles). However, if the customers are further expanded to include the recycling facilities purchasing the different types of processed material, then one might discover that there are preferred or even mandated methods for the delivery of that material. If those methods conflict with design requirements, then the requirements must be challenged.

Tracing a requirement to its original design decision can enable a designer to challenge the requirement by questioning the decision which lead to its creation. Looking at an example from the EAI Combined Collection Vehicle, one can see how original design decisions can be intuitively discovered. As shown earlier, one requirement given to the designers by the client was that the vehicle must shred plastics before storage. This requirement and the details of how it was challenged will be further discussed later in this chapter. By developing a sample functional hierarchy as shown in Figure 6.1, the designer is better able to recognize the underlying design decisions.

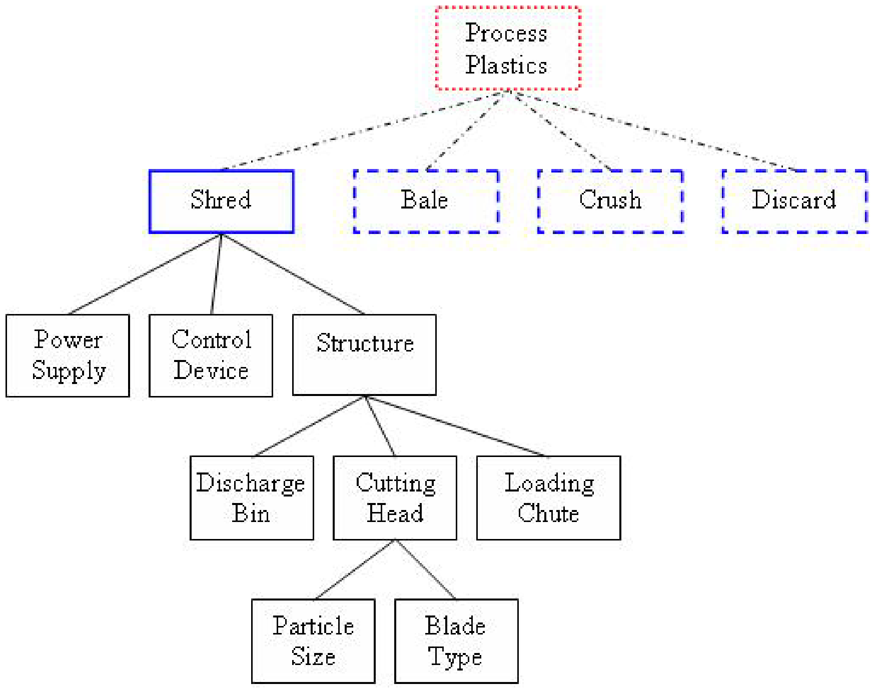


Figure 6.1 - Functional Hierarchy: Process Plastics

Thinking intuitively and working backwards from the requirement to "shred plastics", one can determine that the fundamental requirement is to "process plastics". This could be accomplished by several different methods such as shredding, baling, crushing, or even discarding for example. Thus, we are able to see that the requirement to shred plastic was simply a high level design decision by the client in regards to the method for processing plastics. By working backwards to uncover the fundamental requirements and the high level design decisions made, it may be possible for a designer to challenge those decisions and perhaps change the requirements at the highest level.

These three concepts have been extracted from different views of the project. They will be illustrated through the discussion of challenging the shredding requirement for material processing and demonstrating the feasibility of baling recyclable material. This shredding requirement was identified as an area for further examination as a result of evaluation of the Baler Design concept explained earlier that was less complex, more efficient, and cheaper to maintain than the other concepts generated. However, it failed the constraint of shredding recyclables. Consequently, this meant it failed the requirement that recyclable material must be removed from the vehicle by vacuum. However, if the requirement of shredding recyclable material was changed or eliminated then the subsequent vacuum requirement could be as well. Thus, in order for the Baler Design concept to be acceptable, the design team had to prove to the client that the shredding requirement was unnecessary.

Processing Recyclables: Baling vs. Shredding/Crushing

Investigation into recyclable processing and conversations with various recycling firms indicated that they are willing to accept recyclables in both shredded and baled form; specifically aluminum, PET, and HDPE plastics. Recycling steel was determined to be relatively unproblematic due to loose processing standards and low collection volumes. Additionally, the team was informed that a system capable of processing aluminum and plastic could also handle steel cans. Therefore, the analysis focused specifically on the processing of aluminum and plastic due to higher collection volumes, greater revenue generation, and the more stringent processing standards. Aluminum has particularly strict standards due to the large volumes, relatively high value of the material, and the large industry involvement from companies like Alcoa[12]. These standards will be discussed later in the chapter.

In general, there are significant differences between the amount of processing required, the equipment used to process the material, and the method for handling. In order to assess the feasibility of the two methods, one must define baling and shredding and evaluate the positives and negatives of each process. Then one must take a look at how these two processing methods could be accomplished onboard the collection vehicle.

Baling

Recycler's World[13] presents definitions for aluminum and plastic recyclables. These definitions are used to correlate "spot market prices" to materials processed in different forms. The prices are presented in pounds per dollar for two different quantities: Less Than Truck Load (LTL) and Truck Load (TL); where a TL is 40,000 pounds or more and LTL is considered as any amount less than 40,000 pounds. Typically, the proceeds in pounds per dollar are greatest for a full truck load. PET and HDPE plastic baled recyclables are defined as follows:

> *Assorted PET bottles or containers compacted into secure bundles with a minimum weight density of 10 lb./cubic foot. May contain Post Consumer PET Soda Bottles of mixed colors.*

And

[12] http://www.alcoa.com/global/en/home.asp accessed November 20, 2009
[13] http://recycle.net/ accessed February 23, 2007

HDPE Mixed Postconsumer Scrap (baled) shall consist of assorted High Density Polyethylene (HDPE) bottle and container scrap compacted into secure bundles with a minimum weight density of 10 lb./cubic foot.

Due to the nature of the curbside collection process, the aluminum collected by the vehicle will be primarily used beverage cans. Recycler's World defines baled aluminum UBC (used beverage cans) as follows:

Baled UBC shall consist of magnetically separated Used Beverage Cans that have been compressed into bales. Baled densities must be a minimum of 14 LBS. per cubic foot. Bale dimensions can range from 24" to 40" x 30" to 52" x 40" to 84"

The process for creating these bales involves compressing the recyclable material through the use of a ram, traditionally hydraulic powered, in a cuboid container. This is the method currently employed on the prototype collection vehicle for processing cardboard and newspaper. Once a full bin of compressed material is realized, the densified mass is strapped tightly with multiple steel bands. Once the baled material is securely strapped, it is removed from the baling apparatus and stored until being transported to a recycling facility. It is expected that these bales will be offloaded from the truck with a forklift and stored in a centralized location to realize maximum market value by being able to sell a full truck load to the recycling facilities, more than 40,000 lbs at one time.

Bales must meet density and dimensional guidelines in addition to being strapped properly with the correct baling wire. According to a conversation which took place in January 2006 with a representative from International Baler[14], plastic bales should be wrapped with six to ten bands per bail. Additionally, the representative explained that plastic bales should be wrapped with 10 to 12 gauge galvanized baling wire. Explaining that 10/18 wire is ideal for PET plastic, where 18 represents the hardness of the wire. This is because of an occurrence known in the industry as “spring back”, where the compressed container does not deform completely plastically and tries to partially return to its original shape. It is this phenomenon that makes baling PET plastic significantly more difficult than cardboard or even HDPE plastic. Similarly, aluminum bales must be strapped with ¾ in. x 0.030 inch (5056-H36) aluminum, 5/8 in. x 0.20 in. steel, 10-gauge (5056-0) aluminum or 13-gauge steel bands (Alcoa, 2004). Thus, special care should be given to the end conditions (density and dimensions) of the bales in order to ensure marketability of the processed materials to recycling companies.

In order to better understand the advantages and disadvantages of baling recyclable material, the method was analyzed in greater detail. The positives and negatives were identified and organized in a list for evaluation. These characteristics were identified based on material definitions, industry standards, and observations gathered from the creation of the two concept designs introduced earlier. Individual lists of pros and cons were created as they relate to the collection vehicle and the curbside collection industry.

Pros:

- Flexible processing capabilities – since the baling mechanisms for paper, cardboard, aluminum, and plastics are almost identical, a processing system that is

[14] http://intl-baler.com/ accessed November 20, 2009

made up of a number of balers would be flexible enough to handle almost any mix of recyclables

- Different markets – the significant increase in truck flexibility will make the truck more desirable in a wider market range; trucks will be able to service residential, commercial, institutional, and entertainment venues which will make them more appealing than the residential-focused current prototype
- Single processing type on truck – a simplification of the systems would mean a reduction of the maintenance and training needs; the use of homogeneous balers may also allow for the elimination of the truck generator in favor of a single hydraulic system
- Currently accepted technology – the current prototype truck paper and cardboard balers are known to function acceptably, and their adaptation to plastic and aluminum use is expected to be relatively straightforward based on conversations with baling company representatives
- Can operate from any off-loading site – since bales could be offloaded by forklift, the operating site does not need any specialized facilities. The relative simplicity in handling bales means that the truck could utilize a "mobile offloading site"
- No added processing to resale – recyclable material does not require secondary processing, cleaning, or packaging
- Reduced development cost – it is expected that the balers used in the system may differ in size and construction, but remain similar in most other characteristics,

such as function and operation. This can dramatically reduce the cost and time necessary for development

- Higher resale value for aluminum – baled UBC (used beverage containers) has a higher market price than shredded UBC according to spot market prices from Recyclers World and is one of the highest revenue generating recyclable materials
- Widely accepted method of sales – this is as opposed to the lack of standardization of flake size and acceptable contamination levels
- Ability to Guarantee Quality – a municipality can definitively inform a recycling firm how the recyclable material will be delivered rather than estimating contamination rates or trying to tailor flake size
- Higher processed material density – we expect that baled plastic and aluminum will have a higher density than the shredded forms, this means less volume will need to be occupied while storing to a full truck load (40,000 lbs) for efficient transport

Cons:

- Limited configurations for storage and transportation – the balers are large and cannot be arranged in many configurations, especially when utilizing a shared ram head between bins
- Higher construction cost – the necessarily large dimensions of bailers and high required load handling capability may lead to higher construction costs, due primarily to materials and welding

- Increased vehicle size – the relatively large size of balers hinders the ability to reduce overall truck width and/or length
- Increased vehicle weight – a robust baler design may result in higher weights than other processing methods

From the lists, it was evident that baling excelled in the areas of flexibility, simplicity, and revenue generation. The uniform processing method simplifies the collection vehicle while enabling it to process different mixes of recyclables, in addition to increasing its capability to service other markets and industries. Also, the ease of handling bales makes it possible for the vehicle to be serviced by a standard forklift at a simple and potentially mobile off-loading facility. Finally, the use of balers lends itself to higher material values and better acceptability due to standardization and higher processed material densities.

The greatest determent to baling appears to be vehicle size and weight. The relatively large size and robust design of balers limits the configuration possibilities onboard the truck. This could necessitate a larger vehicle platform or a greater number of axles to distribute increased weight.

Shredding

The definitions of shredded plastics and aluminum are not as clear as one might expect. Again, Recycler's World offers definitions related to their spot market prices:

> *Shredded UBC shall consist of aluminum Used Beverage Cans that have been magnetically separated and shredded into uniform material handleable (pneumatic) state. The shredded UBC shall have a minimum density of 12 LBS. (pounds) per cubic*

foot and a maximum weight density of 17 LBS. per cubic foot. Must be free of excessive fine material under 4 mesh in size. Must be free of other metals and foreign material.

While,

Colored PET Regrind shall consist of reground sorted colored PET bottles or containers.

And,

HDPE Mixed Postconsumer Scrap (loose) shall consist of reground flake of assorted High Density Polyethylene (HDPE) bottle and container scrap.

Although aluminum shredded UBC has a specific minimum size, the maximum size is subject to change or interpretation. What is a material handle-able state to some companies may not be to others. This could be a matter of judgment or a result of the equipment and processing methods employed by a given recycling facility.

The definitions for shredded plastics are even more unclear and open to interpretation. The problem lies in the fact that there does not seem to be an industry standard regarding the size of the flakes that are designated as regrind. For example, a representative from Canusa Hershman Recycling Company[15] mentioned that they prefer regrind flakes to be about 3/8" in diameter. A representative from Polychem USA[16] considered regrind to be about 1/8" in size. More over, there is not an apparent standard for flake quality or the method used to produce such quality. This information varies from one recycling company to another as regrind is traditionally produced at the recycling facilities in-house from delivered plastic bales. Thus, there is very little

[15] http://www.chrecycling.com/ accessed November 20, 2009
[16] http://www.polychem-usa.com/ accessed November 20. 2009

information regarding a commercial standard for producing and cleaning the regrind flakes, as well as an established method for transporting them to the recycling facilities.

A shredding system on the truck would operate similar to the units on the prototype vehicle, where sorted plastics are fed into chutes and engaged by a shredding mechanism that tears or cuts the material into smaller flakes, which are collected in a bin. The recyclables would be offloaded from the vehicle to a centralized location. EAI envisions this process being accomplished by an industrial vacuum system. However, the recyclables would have to be dried, potentially by blowing hot air into the bin, before they could be vacuumed from the collection truck. Once removed, they would have to be run through some type of cleaning process to rid them of contamination and increase the likelihood that the recycling facilities would accept them. To realize maximum market price, the material would stored until more than 40,000 lbs could be sold at one time. A packaging method would have to be developed to contain the shredded plastic, which was both cost effective and acceptable by the recycling facilities.

Similar to baling, an analysis of shredding recyclable material was created to better quantify the results and clarify which method is the most desirable. The reasons for and against shredding were identified in individual lists of pros and cons.

Pros:

- <u>Flexible configurations of storage on truck</u> – flakes or regrind allow for processed material to be stored in geometrically asymmetric containers
- <u>Guarantee standard package size</u> – packaging would be created at a standard off-loading location from loose flake

- Rapid off-loading – due to the use of a quick-connect vacuum system at the off-loading site
- Low human interaction – the use of a quick connect vacuum system reduces the amount of human involvement in offloading the material from the truck
- Decreased vehicle weight – generally, shredder equipment weighs less than baling equipment

Cons:

- Unpredictable resale values – variance in the flake size and level of contamination accepted by different recycling companies. Thus, the acceptance of the material and/or price paid cannot be accurately predicted
- Requires packaging for bales – since the shredded material cannot be secured by straps, like traditional bales, a packaging system would have to be developed. Many recycling companies have restrictions on what packaging materials are acceptable.
- Lower processed material density –requires greater vehicle storage space due to relatively lower processed material densities
- Requires a specialized and custom off-loading site – for efficient removal of material from the vehicle, such as by industrial vacuum, and additional material processing to clean the flakes, remove contamination, and package for transport

Shredding material appeared to be beneficial in terms of on-board material storage and material off-loading. The ability to handle processed material quickly and with low human involvement, such as the idea presented by EAI of using an industrial vacuum, is desirable. However, it comes at the cost of a highly specialized off-loading facility and is off-set by the need for secondary processing to clean and package the material. In some cases, such as aluminum recycling, numerous packaging materials are not permitted. Alcoa specifies that skids, shrink-wrapping, metal or wooden boxes, fiber cartons, and fiber or metal drums are not acceptable and aluminum packaged with these materials is subject to rejection (Alcoa, 2004). The most discouraging observation was the unpredictable resale values due to variance in the shredded material standards of different recycling companies.

Comparison Results

After evaluating the advantages and limitations of baling or shredding aluminum and plastic, it appeared that baling was the most desirable processing method. The positives of baling, namely flexibility, simplicity, and revenue generation, were beneficial from both an engineering and business perspective. A uniform processing system, such as hydraulic powered balers, would reduce complexity in terms of design, maintenance, and operation. Baling would make the collection vehicle easier to integrate into the systems currently in place at municipalities across the country. This is largely due to the simple off-loading requirements and wide industry acceptance of bales. Furthermore, the predictable material revenue generation would increase the vehicles marketability.

The representative contacted at Polychem USA early in the project, who trades in plastics, offered a few recommendations regarding shredding vs. baling. He first suggested that shredding or grinding should not be done by a pre-recycling firm unless they "know what they're doing." He also pointed out that even if the plastics arrive shredded; the recycling firm is probably going to process them again simply because the machinery is set up to feed plastics into a grinder at the beginning of the system. Additionally, this is the only way the firm can ensure the material meets their standards. While handling shredded plastics with a vacuum system would be innovative, if a municipality wants a recycling firm to pick up the plastics it can be expected that the firm prefers to use the current system of bales.

While baling appeared to be the preferred processing method, the concern of storage volume and its relation to vehicle size was still yet to be determined. Thus, analysis was conducted to determine the volume reduction of shredding versus baling recyclables in order to conclude if one method had an advantage over the other. Due to the mobile nature of this vehicle and the need to meet federal vehicle regulations and traverse neighborhood streets, the vehicle size is of great importance. With a requirement of servicing 350 households, one can see that greater volume reductions from processing lead to smaller vehicles.

PET Bottles Volume Reduction Shred vs. Bale

PET plastic bottles were used to compare the volume reduction for shredding versus baling due to their relatively large collection volume, available processing data, and bulky unprocessed form. Additionally, they are considered one of the most difficult materials to condense by baling due to the occurrence of "spring back" introduced earlier.

Data gathered from the 125 house "blue box" test, conducted by EAI with the prototype vehicle, was used to quantify the volume reduction from shredding plastic. Standard EPA volume-to-weight material conversion factors (EPA, 1997) were used to approximate the volume reduction resulting from baling plastic to various densities. The standard volume-to-weight conversion factor of Table 6.1 was used in conjunction with the PET weight collected during the EAI 125-House Blue Box Test to determine the unprocessed volume for 350 houses, see Table 6.2.

Table 6.1 – PET Bottles Standard Volume-to-Weight Conversion

PET bottles	Volume (yd^3)	Weight (lbs.)	Density (lb/ft^3)
Whole bottles (uncompacted)	1.00	35.00	1.30

Table 6.2 - Unprocessed PET Bottle Volume

	EAI-125 House Weight (lbs.)	Density (lb/ft^3)	EAI-125 House Unprocessed Volume (ft^3)	EAI-350 House Unprocessed Volume (ft^3)	EAI-350 House Unprocessed Volume (yd^3)
PET bottles	29.00	1.30	22.31	62.46	2.31

The 350 house unprocessed volume was then used in conjunction with EPA PET whole bottle and baled/compacted bottle densities to determine the resulting processed volume for various compaction densities. As mentioned earlier, a plastic bale must have a minimum density of 10 pounds per cubic foot in order to be accepted by recycling facilities. The estimated volume reductions from shredding and baling plastic for the anticipated collection of 350 households are shown in Table 6.3 and Figure 6.2.

Table 6.3 - PET Bottle Volume Reduction

PET bottles Processing Method	Percent Volume Reduction	350 House Processed Volume (ft^3)	350 House Processed Volume (yd^3)
Shred	65%*	21.86	0.81
Bale - 10lb/ft3 Density	87%	8.12	0.30
Bale - 15lb/ft3 Density	92%	5.00	0.19
Bale - 20lb/ft3 Density	93.50%	4.06	0.15

*calculated from EAI-125 House Blue Box Test

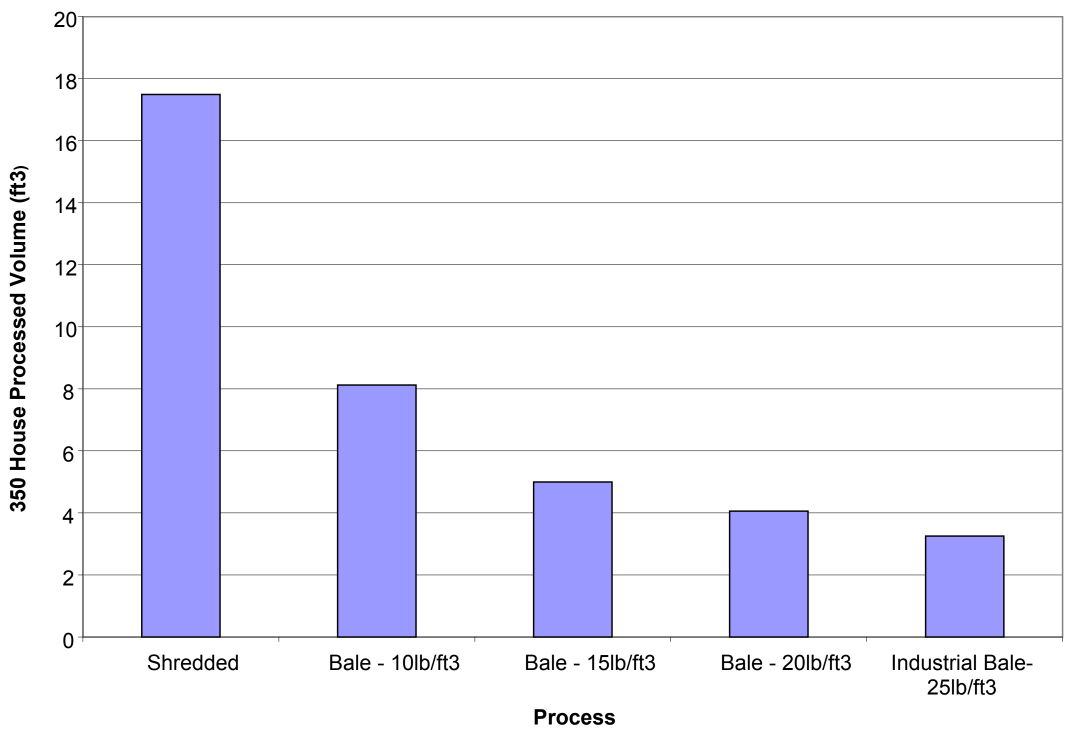


Figure 6.2 - Processed Volumes for Shredding vs. Baling Plastics

The results indicate that a significantly greater volume reduction can be achieved from baling plastic as opposed to shredding. Even at the minimum required density, baling results in more than twice the volume reduction of shredding. Thus, the feasibility of baling recyclables, such as PET, on-board the vehicle had to be determined and quantified.

Feasibility of Baling

Since baling showed a clear advantage over shredding in terms of volume reduction, the next question was whether it was possible to bale recyclables on-board the collection vehicle. Conversations with Mr. Chuck Kelley, President of KSC Inc. in Greenwood, South Carolina, on several occasions in the early stages of the design process indicated that mobile baling on-board a vehicle had never been accomplished. KSC Inc. is a diversified machine shop that previously manufactured industrial balers for International Baler. With over two hundred different baler models, International Baler offers the greatest and most diverse product line in the industry. Mr. Kelley informed the design team that on several past occasions he had conversations with representatives from International Baler in which he proposed the idea of on-vehicle balers and was told without explanation that it simply could not be done. However, C&M Baling Systems[17] in Raleigh, North Carolina informed the research team that they were able to make a satisfactory PET plastic bale from a vertical down-stroke baler. The C&M Baling representative explained that the spring back of HDPE is negligible compared to PET and thus baler design should focus on PET plastic. In other words, *if a system can properly process PET, it can also process HDPE*.

In addition to an extensive selection of standard balers, C&M Baling Systems also engineers and manufactures custom balers. They stated their testing showed that a mixed (with and without bottle caps) PET bale with a density of 17 pounds per cubic foot could be achieved from a vertical down-stroke baler with an 8 inch bore hydraulic cylinder and a ram face pressure of 106 psi. Unfortunately, they were unwilling to share more detailed test results such as ram face and baler bin design. Nevertheless, their results seemed to indicate that on-board baling of plastic could be possible as their testbed baling system was similar in size and design to the balers on the prototype collection vehicle. The team inquired into more specifics of the baler system with the idea of adapting it to the on-board application, but was informed that the design was a self contained, small industrial application design. Therefore, the system would require extensive modification to meet the needs of the on-board baling concept.

With C&M Baling Systems indicating that a PET plastic bale can be made with a vertical down-stroke baler, the research team attempted to produce similar results. Due to cost and availability, the seemingly undersized baling system on the prototype truck was used in an effort to determine the ram face pressure necessary to achieve the minimum required bale density of 10 lbs/ft^3 (see the PET Compacting and Baling Test Proposal in Appendix A). The system on the current truck utilizes a hydraulic ram with a 6 inch bore as opposed to the 8 inch bored used in testing by C&M Baling Systems. Thus, the pushing force and resulting ram face pressure of the baler unit on the prototype truck will be much lower. This lead the team to create a PET test bale in which all bottles had the caps removed. The decision was supported by EAI who is developing a patent related to shredding PET and HDPE plastic for the purposes of recycling. They plan to

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[17] http://www.baling.com/ accessed November 20, 2009

extend or interpret this patent to include a proprietary device that will “shred” the tops off bottles before they are placed into the baler, hopefully eliminating the need for manual removal. Additionally, the removal of the bottle caps should eliminate the need for excessively high ram face pressures required to burst bottles with caps in place. The team also envisioned the removal of the bottle caps as a potential revenue generator due to the reduction in bale contamination. This specific recommendation is the subject of testing and is verified, as will be discussed later.

Although PET plastic was identified as the most difficult material to bale, the ability to bale aluminum was also critical. Aluminum has more stringent dimensional specifications and a 40% greater minimum required density of 14 lbs/ft^3. With the desire to use a multi-bin baler with a shared translating ram face, the system would need to be able to produce satisfactory bales of plastics and aluminum with the same hydraulic cylinder and ram face. Therefore, testing was also conducted to determine if a single system could produce acceptable bales of both materials.

Bale Testing

The feasibility of on-board baling was determined through testing with the currently vehicle prototypes baler systems. These systems were originally designed for processing cardboard and paper, where the primary function of the baler is to remove voids through compaction of the material. Relatively little force is required to successfully accomplish this task. However, in the case of baling plastic or aluminum, the baler must be capable of physically crushing whole containers. One can relate this difference to compacting a cardboard box by stepping on it and applying one's body weight, versus forcefully stomping on a plastic bottle or aluminum soda can in order to reduce its size. The success of the relatively small and lightweight balers of the prototype vehicle at processing plastic and aluminum is used to determine the feasibility of on-board baling.

Two tests were conducted: one for PET plastic bottles and one for aluminum cans. These tests utilized recyclable material obtained from the Clemson University Kite Hill Recycling Facility. This material, PET plastic bottles and aluminum cans, was donated for the research purposes. The tests were conducted on-board the prototype collection vehicle with the PET plastic test taking place at the EAI facility in Greenwood, SC and the aluminum can test occurring on the premises of the Kite Hill facility.

The details of the single hydraulic cylinder vertical down-stroke baler system used for the tests are listed below. As stated earlier, the hydraulic cylinder bore and resulting ram face pressure of this system are less than those utilized by C&M Baler to successfully create an acceptable PET plastic bale.

<u>Prototype Truck Baling System Specifications:</u>

- 6" bore hydraulic cylinder (*8" bore C&M Baler*)
- 24" stroke
- 1600psi regulated hydraulic line pressure
- Approx. 45,000lbs. of compacting force
- 30" x 28" ram face (Area=840 in.^{2})
- Approx. 54psi ram face pressure (*106 psi C&M Baler*)
- 30" x 28" x 43" interior baler bin dimensions

The hydraulic system was designed for line pressures of greater than 2000psi but the system was regulated to only 1600psi at the time of the test and the design team decided not to change it.

PET Bale Test

The first of the two bale tests was conducted on PET plastic bottles in order to determine the density that could be achieved from the prototype baler system. While commercially available plastic baling units easily exceed the minimum required bale density of 10 pounds per cubic foot, those units are much larger than the ones found on the prototype vehicle and are traditionally horizontal-stroke with multiple cylinders. The test was conducted using PET plastic as opposed to HDPE plastic because it has the greatest "spring back" or rebound after compression, making it one of the most difficult materials to bale. Therefore, the results represent a worst case scenario and higher densities should be able to be achieved for HDPE plastic, which has relatively little rebound.

Although the ram face pressure is roughly half of that obtained by C&M Baler, the bottles used in this test all had the caps removed, which the team hoped would significantly reduce the pressure required to create a satisfactory bale. This serves as an accurate representation of the bottles the collection vehicle will process as EAI plans to extend their patent on shredding plastics to include a fast, simple, and safe process for "shredding" the bottle caps from the bottles before baling.

The test was conducted by three students from the research team: Peter Johnston, Stuart Miller, and Eddie Smith. Operating instructions for the vehicles hydraulic baler system and general supervision were provided by Larry Aldridge of EAI. The uncompacted PET plastic bottles provided by Kite Hill were gathered in trash bags and transported to the EAI facility where the test took place in a 12 x 8 x 8 foot box truck as shown in Figure 6.3.

Figure 6.3 - Uncompacted PET Plastic Bottles

Approximately 160 cubic feet of un-compacted whole PET bottles were used for this test. This represents roughly 2.5 times the calculated volume generated weekly by 350 households (62.5ft^3).

The procedure for the test consisted of two students standing outside the truck, extracting bottles from the trash bags and removing the caps manually. The third person, standing inside the truck, placed the bottles into the baler bin until full. Once the bin was full, the ram head was positioned over the top of the bin and the hydraulic cylinder was engaged to compact the bottles. The hydraulic line pressure just before the cylinders full stroke was recorded. After holding the material compacted for ten seconds, the cylinder was reversed and the ram head was slid away from the top of the bin. Then the distance from the top of the compacted material to the top of the bin was recorded. This process was repeated until all of the test material was consumed or the baler bin was full.

The specific procedure followed for this test is outlined in Appendix B, while the original proposed tests can be found in Appendix A. Due to restrictions on time and the availability of plastic bottles for testing, this was the only PET bale test conducted.

PET Test Results

The bale created from the PET Bale Test, see Figure 6.4, had a weight of 208 pounds with dimensions of 24 x 28 x 30 inches, resulting in a density of roughly 17 pounds per cubic foot. Therefore, it far exceeded the minimum required density of 10 pounds per cubic foot specified by Recycler’s World and would thus be widely accepted by recycling facilities. The test proved that it is feasible to bale plastic in a mobile, on-vehicle application with a relatively small vertical down-stroke baler system.

Figure 6.4 - PET Plastic Bale

It is important to note that the test bale created has the same density as that achieved by C&M Baler during their testing, even though the ram face pressure was significantly less. This is clearly a direct result of removing the caps from the bottles, see Figure 6.5. Potentially even greater densities could be achieved with increased ram face pressures from the use of greater hydraulic line pressure or a larger bore hydraulic cylinder. However, testing still needs to be done to confirm.

Figure 6.5 - Baled PET Bottles

In order to create the test bale, the baler bin was filled and compacted 27 times, with the 27th time representing the final compaction after inserting the cardboard and baler tie straps. The distance between the PET plastic and the top of the baler bin was measured after each compaction stroke and is shown in Figure 6.6.

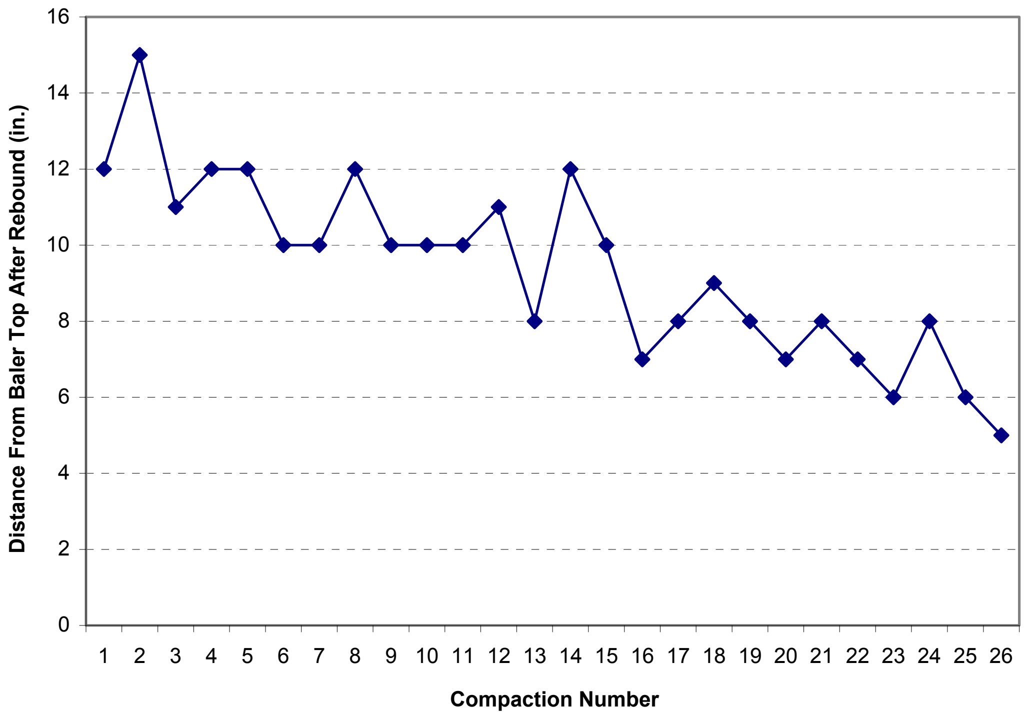

Figure 6.6 - Distance From PET Plastic to Top of Baler Bin After Rebound

The measurement data of the distance from the plastic to the top of the bin illustrated the fill rate of the bin, accounting for material spring back. It also indicated how much volume was available for whole uncompacted bottles to be added to the bin after each compaction, which is related to the number of households that can be serviced between compactions. After each compaction, the spring back of the material was visible as the material could be seen rising up the bin wall as the ram face was retracted. The results indicate that either a taller bin or greater crushing pressure would be needed to create larger bales. Increased material densities could resist spring back and allow the baler bins to be filled closer to the top before final compaction and strapping, producing larger bales from the same bin. Further testing is needed to verify that increased ram face pressure would compact the bottles sufficiently to reduce spring back.

For this test hydraulic line pressure was mechanically regulated to a maximum of 1600 psi. The hydraulic line pressures for each compaction, noted just before the cylinder reached full stroke, are illustrated in Figure 6.7.

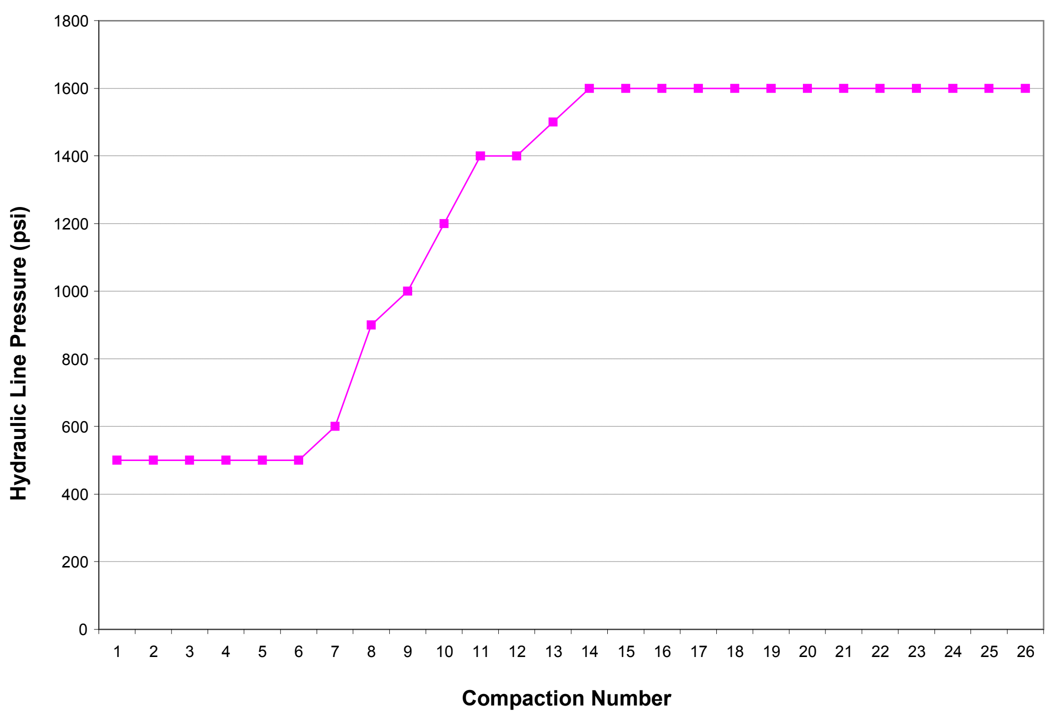

Figure 6.7 - Baler Ram Hydraulic Line Pressure vs. Compaction Number

Observation of the compacted bottles indicated that greater pressure could have produced greater reduction in size which would increase bale density, helping to reduce spring back, and provide more space to fill the bin between compactions. This would help to reduce the number of compactions necessary to create a complete bale and potentially increase the bale size that could be realized. Increased line pressure would result in greater ram face pressure and likely greater compaction ratios from the relatively undersized 6” bore system. Greater ram face pressures could also be achieved with a larger bore hydraulic cylinder, such as the 8” bore cylinder used by C&M Baler, while keeping line pressures relatively low. Comparing Figure 6.6 and Figure 6.7, it is evident the volume of compressed material in the bin continued to increase and the distance of PET from top of baler bin decreased after maximum hydraulic line pressure was reached at compaction number 14. This indicated that a maximum in achievable bale density had been reached with the current setup at compaction number 14. Therefore, greater ram face pressures from increased hydraulic line pressure or larger cylinder bore diameters could potentially achieve higher material densities. This would allow the collection vehicle to service more homes for a given baler size.

It is important to remember that all containers had the caps removed prior to being placed in the baler in order to increase the compressibility of the material. This is critical to achieving the required density with the relatively small balers on the truck because the bottles are not run through a perforating mechanism before compaction and the hydraulic ram does not generate enough force to burst the containers if the caps are left in place. An apparatus may be developed for the vehicle, in compliance with the patent held by EAI, which will remove or “shred” the caps from the containers automatically before insertion into the baler bin. This process will ensure repeatable bale densities and reduce the level of contamination of the final bales be eliminating the bottle caps.

From these test results it is obvious that plastic can be successfully baled onboard the truck with a system similar to that of the current prototype vehicle. It is also apparent that increasing the hydraulic ram force and thus the ram face pressure could potentially increase the achievable bale density and size, while decreasing the number of required compactions. These benefits could be realized through the design of a baling system utilizing a hydraulic ram with a larger nominal bore and or increased hydraulic line pressure. Additionally, larger baler bins could be implemented to increase the achievable bale size and thus the marketability of the bales; if vehicle space permits.

Aluminum Bale Test

In addition to the PET Bale Test, a similar test was conducted with whole aluminum used beverage cans. This test was conducted in order to determine if a mobile baler system could satisfy the Alcoa aluminum baling standards (Alcoa, 2004). Specifically, the team was interested in the baler's ability to exceed the minimum required density of 14 pounds per cubic foot. Aluminum is the greatest revenue generating recyclable material on a per pound basis that this truck will collect. Thus, it is critical that the baler system can create satisfactory bales.

The test was conducted by two students from the research team: Peter Johnston and Eddie Smith. Operating instructions for the vehicles hydraulic baler system were provided by Larry Aldridge of EAI. Similar to the PET bale test, the whole aluminum used beverage cans were provided by the Kite Hill Recycling Facility. However, this test was conducted on the Kite Hill premises as opposed to the EAI facility. The aluminum cans were supplied by Kite Hill in large roll away containers measuring three feet deep, three feet across, and five feet in length. Due to limited material availability, only two containers were supplied for this test, resulting in approximately 90 cubic feet of uncompacted aluminum cans.

The procedure for the test consisted of one student standing outside the truck, extracting cans from the bins and handing them to the other student located in the vehicle. That person then placed the cans into the baler bin until full. Once the bin was full, the ram head was positioned over the top of the bin and the hydraulic cylinder was engaged to compact the cans. Once the cylinder reached full stroke or maximum hydraulic line pressure, the cylinder was reversed and the ram head slid away from the top of the bin. This process was repeated until the material was consumed and the cylinder failed to reach full stroke, indicating that maximum system density had been reached.

The specific procedure followed for this test is outlined in Appendix C. Due to restrictions on time and material availability, this was the only aluminum bale test conducted. Unfortunately, Kite Hill was not able to provide enough material to create a complete bale. However, the team was able to create a tall enough bale to quantify material density and system performance.

Aluminum Test Results

The bale created from the Aluminum Bale Test had an approximate weight of 207 pounds with dimensions of 28 x 30 x 26 inches, resulting in a density of about 16.4 pounds per cubic foot. Thus, the density exceeded the minimum requirement of 14 pounds per cubic foot set by Alcoa. While the test bale did not fully satisfy the Alcoa dimensional and volume standards due to the relatively small baler bin size on the prototype vehicle and the lack of material, the results are promising that a larger baler could meet all requirements.

The bale weight and density were estimated based on standard EPA conversion factors due to an inability to remove and weight the bale after testing. This was due to the lack of necessary equipment for removal and weighing of the bale at the Kite Hill facility. As the vehicle is just a prototype, the current removal system is very primitive and requires a great deal of effort and external assistance to remove the bale. Additionally, a forklift for transporting the bale and scales for weighing were not available. A standard volume-to-weight conversion factor from the EPA, see Table 6.4, was used to quantify the weight of the final bale.

Table 6.4 - Aluminum Cans Standard Volume-to-Weight Conversion

Aluminum Cans	Volume (yd^3)	Weight (lbs.)	Density (lb/ft^3)
Whole cans (uncompacted)	1.00	62.50	2.3

Approximately 90 cubic feet of uncompacted aluminum cans were fed into the baler bin. This was based on completely emptying two full roll away containers provided by the recycling facility that measured 3 x 3 x 5 feet each. Therefore, the total weight of aluminum processed into the bale was approximately 207 pounds based on the standard density of 2.3 pounds per cubic foot. The final bale dimensions of 28 x 30 x 26 inches were measured with the bale in the bin and resulted in the compacted material density of roughly 16.4 pounds per cubic foot.

Alcoa requires a minimum bale volume of 30 cubic feet and bale dimensions in the following ranges: [24 to 40”] x [30 to 52”] x [40 to 72”]. These requirements were not fully met by the prototype baler system due to its relatively small size and the availability of only 90 cubic feet of aluminum cans. In order to meet these volume and dimension requirements, a larger baler bin would be required. This would necessitate a large ram face, which would lower ram face pressure given the same nominal bore hydraulic cylinder and hydraulic line pressure. However, the current system exceeded the requirements by greater than 2 ft^3 with a 6” bore hydraulic cylinder and a maximum 1,600 psi line pressure. A larger bore cylinder, such as the 8” cylinder used by C&M Baler, and greater hydraulic line pressure would compensate for the use of a bigger ram face and still produce satisfactory material densities. Therefore, the design team is confident in the ability of an on-vehicle vertical down-stroke baler to meet all aluminum bale requirements. Testing of a larger prototype baler system is needed to verify.

Pricing

In order to determine the financial impact of different processing methods, material spot market prices from Recyclers World were compared. Spot market prices were compared for two different levels of sorting at two different time periods. This provided a good view of the overall relationship of price and processing method.

Initially, prices were compared for sorted color postconsumer plastics as the client’s original vision for the collection vehicle entailed a high level of sorting for all processed materials. Sorted color postconsumer plastics are those which have been sorted into a single color. Spot market prices from January 2006 for regrind and baled plastics are illustrated in Table 6.5 below. The prices shown are for a full truck load (40,000 pounds). Aluminum prices are also included to highlight the greater revenue generation and advantage of baling.

Table 6.5 – Comparison of Sorted Color Postconsumer Spot Market Prices, January 2006

Material	Sorted Color Postconsumer Regrind ($/lbs)	Sorted Color Postconsumer Scrap - Baled ($/lbs)
PET	0.45	0.32
HDPE	0.37	0.24
Aluminum	0.75	0.78

It must be noted that the value of plastic regrind is higher than what can be processed on the truck. As discussed previously, regrind is sorted, washed, and ground to the specification of a recycling firm. It contains very little contamination from paper labels or other plastics and acceptable standards vary among recycling firms. Achieving this level of processing on-board the collection vehicle is unrealistic. Thus, the price paid for the shredded (or even specifically ground) plastic produced on the truck would be considerably less than the values in Table 6.5.

The comparison of sorted color postconsumer plastics shows that greater revenue could be generated from regrind as opposed to baled processing. However, as explained above, this is an unrealistic level of processing to expect from on-board the collection vehicle. The cost of the additional material processing necessary to realize the regrind market prices would outweigh any revenue increase as compared to baling. Baling represents an achievable alternative processing method that will generate steady and predictable revenue. Furthermore, baling of aluminum cans will result in greater revenue generation than shredding. Aluminum brings roughly twice the price per pound of plastics, making a reliable processing method critically important.

Design development revealed that it would be difficult to reliably sort materials on-board the truck with the allotted time and personnel while achieving the required level of accuracy. Vehicle space constraints for the required number of balers or shredders to handle individually color sorted materials were also a concern. Therefore, a comparison of mixed postconsumer plastics was conducted, see Table 6.6. Mixed postconsumer plastics are not color sorted, which enables faster processing and the use of less equipment. This helps to increase the flexibility of the vehicle, making it capable of processing a larger volume of recyclables in the same relative time.

Table 6.6 - Comparison of Mixed Postconsumer Spot Market Prices, June 2009

Material	**Mixed Postconsumer Regrind ($/lbs)**	Sorted Color Postconsumer Regrind ($/lbs)	**Mixed Postconsumer Scrap - Baled ($/lbs)**	Sorted Color Postconsumer Scrap - Baled ($/lbs)
PET	**NA**	0.27	**0.17**	0.19
HDPE	**0.24**	0.26	**0.15**	0.17
Aluminum	**0.49**	NA	**0.51**	NA

Prices for sorted color postconumer plastics were shown for reference due to the long time between comparisons of prices. Material prices fluctuate greatly due to principles of supply and demand, macro economics, as well as commodity price speculating. This is highlighted by the greater than 30% drop in the price of aluminum from 2006 to 2009. However, the overall trends between regrind and baled materials are unchanged.

The spot market prices for PET and HDPE illustrate that the difference in price per pound for mixed versus sorted color material is minimal. Therefore, the benefits in vehicle flexibility realized by mixed material processing far outweigh the relatively insignificant price difference. The same price trends illustrated for 2006 sorted color postconsumer plastics are evident for the 2009 mixed postconsumer plastics. Regrind plastic brings a higher price per pound than baled plastic, while aluminum generates more revenue when baled. Thus, the reliable processing method of baling could be coupled with the collection of mixed postconsumer materials without any significant decrease in revenue generation. However, the price per pound that could be realized from the bales made on-board the vehicle needed to be quantified relative to the more standard industrial sized bales.

Comparison of PET Bale Revenues

Upon completion of the PET baling test, United[18] and Evergreen[19] Plastic Companies were contacted in early 2006 to determine the cost difference between the bale created during testing and a standard industrial bale. Both companies stated that they would accept the bales while one mentioned that they would provide greater compensation than standard commercial bales due to the low contamination from the removal of the bottle caps. The specifications for the two bale scenarios, the test bale created and an industrial bale, are detailed below.

[18] http://www.usplastic.com/catalog/default.asp
[19] http://www.polychem.com/evergreen/

Scenario 1: Processed Bale
Mixed, Post-consumer PET with labels
Caps removed
Bale Dimensions: 24"x28"x30"
Bale Weight: 208 lb
Bale Density: 17 lb/ft^3

Scenario 2: Industrial Bale
Mixed, Post-consumer PET with labels
Caps in place
Bale Dimensions: 30"x45"x64"
Bale Weight: 800 lb
Bale Density: 16 lb/ft^3

Both companies were quick to respond with two different opinions on the total cost for each of the bale scenarios. United Plastics Co. quoted a price of 0.20-0.25 $\frac{\$}{lb}$ and 0.18-0.23 $\frac{\$}{lb}$ for scenarios 1 and 2, respectively. United determined that since the smaller bales contained bottles without caps, therefore reducing the level of contamination, they are more valuable in the market. Evergreen Plastics on the other hand, quoted a price of 0.12 $\frac{\$}{lb}$ for scenario 1 and 0.165 $\frac{\$}{lb}$ for scenario 2. Evergreen Plastics stated that "the bales are very labor intensive" due to their small size, therefore reducing the overall cost of the bale per pound. Assuming that these quotes demonstrate the high and low ends for the PET bale cost, the average value of our processed bale is 0.16-0.18 $\frac{\$}{lb}$ and 0.17-0.19 $\frac{\$}{lb}$ for an industrial sized bale. As shown above, the industrial sized bale only fetches 1 cent more per pound than our processed bale. For every one hundred pounds of processed PET, the industrial bale makes $1 more than our proposed bale, creating a $400 difference in cost when a 40,000lb truckload of PET is delivered.

It is important to note that the actual production bales will be larger than the test bale produced as it was not a full size bale. Additionally, the production balers will be larger than those on the prototype vehicle in order to meet the aluminum bale dimensional requirements. Based on the information obtained, the larger bales could fetch as much or more than industrial bales. This is due to the fact that the larger bale size will alleviate some of the concerns expressed by companies such as Evergreen regarding labor intensive handling, while maintaining the low level of contamination that makes the bales attractive to companies like United Plastics.

Refined Requirement

The original requirement that the collection vehicle must "shred" and "crush" certain recyclables was successfully refined to the requirement that the vehicle must simply "process recyclables". This was accomplished through testing, defining more customers and refining their needs, and breaking down the requirement to its original design decision.

The requirement to shred and crush recyclables represented a solution based design decision at the highest level. Through the use of an alternative solution, baling, the design team was able to challenge that decision. Testing illustrated the feasibility of baling, while identifying the recycling collection facilities as customers revealed new customer needs. Not only did the recycling facilities have varying standards for shredded or regrind plastics, but they preferred recyclable material in baled form. This demonstrated that the alternate solution was not only feasible, but favored.

Demonstrating the feasibility of another solution provided proof that the requirement was solution based and thus, overly narrowed the design scope. This justified the reinterpretation of the requirement. Removing the solution from the requirement revealed that the real underlying requirement was to process recyclable materials on-board the vehicle into a form which was saleable to recycling collection facilities. Thus, the original requirement to shred and crush recyclables was not replaced with baling, but made independent of the solution.

CHAPTER 7

CASCADE EFFECT OF CHALLENGING SHREDDING/CRUSHING REQUIREMENT

Successfully challenging the requirement to shred and crush certain recyclables had a direct impact on other requirements. Some were eliminated due to being solution based, while others were revised based on the latest recycling data. Ultimately, the revision of the recyclable processing requirement resulted in a new list of requirements which were independent of the solution and based on the latest recycling data and practices. This cascade effect, the result of removing the solution from the requirement of processing recyclables, thus prompted other requirements to be revised and eliminated.

By revising a requirement such that it is independent of the solution, other solution dependent requirements are easily recognized. Additionally, successfully challenging a requirement can give the client the ability to look at other requirements more objectively and revisit their underlying design decisions. Since requirements are ultimately design decisions at the highest level, the client can immediately recognize these decisions. They can then be reevaluated based on available data and findings, such as recycling practices, recyclable volume, and the value of recyclables.

Recyclables Removed by Vacuum

The requirements that “recyclables must be removed by industrial vacuum” and “fluid must be removed from recyclables before vacuuming” were revisited as a result of reinterpreting the recyclable processing requirement. Removing the solution based design decision to shred and crush recyclables from the recyclable processing requirement revealed that the vacuuming requirements were heavily solution dependent. If recyclables were not processed into small pieces by shredding or crushing, then they could not feasibly be removed by a vacuum system. In addition, if vacuuming was not feasible then the requirement to remove fluid from the recyclables before vacuuming was no longer applicable. Thus, making the recyclable processing requirement solution independent meant that the vacuum requirements could be eliminated.

It is important to note that removing the requirement that recyclable materials must be removed by industrial vacuum does not mean this is not a viable design solution. For example, if it was decided to shred recyclables, then removal by industrial vacuum would be a feasible and potentially preferable design solution. Making requirements independent of the solution promotes creativity in design which can lead to new and innovative solutions. Therefore, the goal of revising and eliminating requirements should always be to promote design creativity while providing guiding principles which maintain the design objective.

Separately Store Eleven Different Categories of Recyclables

One of the requirements of the collection vehicle was that it "must separately store eleven different categories of recyclables, plus trash". This requirement was revisited as a result of the recyclable material collection volume data and the price per pound paid for different material categories. Mandating eleven different recyclable categories meant increased processing capacity, storage space, and personnel involvement. The more categories for which materials have to be sorted, the longer the time required at each residence and the fewer houses the vehicle can service in a given time period. Furthermore, increased processing and storage results in a larger and heavier vehicle that is more complex to maintain.

The separate storage of different recyclables was investigated based on collection volume and price paid for the recyclable categories. Particular focus was given to those recyclable categories with relatively low collection volumes and low value, such as glass. Additionally, highly separated materials, such as HDPE plastic, were evaluated to determine if the separate storage was favorable from an economic and operation perspective.

Separate Collection of Brown, Green, and Clear Glass

Of the eleven different categories of recyclables, three of them were brown, green, and clear glass. These three materials were required to be stored separately. However, the data gathered for glass collection volumes by EAI and the price per ton paid for different colors of glass prompted the client to revisit this requirement.

The EAI 350 household collection volumes, Table 5.1, indicate that the collection volumes for brown and green glass are insignificant compared to clear glass. The volumes for brown, green, and clear glass are shown in Table 7.1 below.

Table 7.1 - EAI 350 Household Glass Collection Volumes

Material	EAI-125 House Weight	Weight to Volume Conversion Factor (ft3/lb)	EAI-125 House Unprocessed Volume (ft3)	EAI-350 House Unprocessed Volume (ft3)
Clear Glass	88.0	0.05	4.0	11.1
Brown Glass	8.1	0.05	0.4	1.0
Green Glass	4.3	0.05	0.2	0.5

Based on the EAI study, the volume of clear glass collected for 350 households is more than ten times that of brown or green glass. The separate collection of all three types of glass will require additional processing equipment and storage compartments on board the vehicle. This will increase vehicle size and weight, in addition to increasing maintenance time and cost. Furthermore, it will increase the operating time due to greater material sorting and processing. Although EAI wants to recycle every piece of material possible, the extremely low collection volumes of brown and green glass do not appear to justify these concessions.

A comparison of brown (amber), green and clear glass material values was conducted to determine if the collection of brown and green glass was warranted from a revenue standpoint. In addition to comparing prices for color sorted glass container scrap, scrap postconsumer container glass was also included. Scrap postconsumer container glass consists of mixed colors of broken or whole container glass. Spot market prices for different categories of scrap glass are shown in Table 7.2 below.

Table 7.2 - Comparison of Glass Spot Market Prices, June 2009

Glass Category	**Spot Market Price**			
	LTL	**TL**	**Units**	**Funds**
Scrap PostConsumer Container Glass	2.00	4.00	ton	USD$
Sorted Clear Container Scrap	8.00	16.00	ton	USD$
Sorted Green Container Scrap	3.00	6.00	ton	USD$
Sorted Amber Container Scrap	4.50	9.00	ton	USD$

LTL = Less than Truck Load Quantity (less than 40,000lbs)
TL = Truck Load Quantity (40,000lbs or more)

The spot market prices for different categories of glass illustrated two important facts. First, clear glass was worth roughly twice that of brown or green glass. Second, mixed glass was worth significantly less than sorted glass. Thus, based on the relatively low collection volumes and price per ton of brown and green glass as compared to clear glass, the requirements to separately store them were eliminated. The requirement to separately store clear glass remained due to the large collection volume and high market value. While storing mixed glass would have the same benefit as clear glass from a processing, maintenance, and operational perspective, spot market prices indicate that it would not be economical to process mixed glass given the relatively low price per ton. Ultimately, the client decided that the revenue generated from only collecting clear glass would outweigh any increase in marketability from the collection all colors of glass.

Separate Collection of Colored HDPE Containers

The requirements to separately shred and store both clear and white HDPE plastics were also revisited. With relatively high collection volumes, based on the EAI study, the decision of what HDPE categories to process was critical. The clients original design decision was that separately processing white and clear HDPE would result in greater revenue despite the increase in sorting and processing time. A comparison of HDPE spot market prices was conducted in November 2005 for clear, white, sorted color, and mixed regrind, based on the current prototype vehicles shredder system. The results are shown in Table 7.3 below:

Table 7.3 – Comparison of HDPE Spot Market Prices, November 2005

HDPE Grade	**Spot Market Price**			
	LTL	**TL**	**Units**	**Funds**
HDPE Mixed Regrind	0.22	0.36	lbs	USD$
HDPE Sorted Color Regrind	0.23	0.39	lbs	USD$
HDPE White Regrind	0.25	0.42	lbs	USD$
HDPE Clear Regrind	0.27	0.45	lbs	USD$

LTL = Less than Truck Load Quantity (less than 40,000lbs)
TL = Truck Load Quantity (40,000lbs or more)

HDPE spot market prices indicated that the difference between mixed regrind and regrind sorted by color was relatively small. At just a few cents less per pound, the collection of mixed regrind was supported by the reduction in material processing time, operator sorting time, vehicle size, and weight. The EAI study sorted HPDE containers by type, namely milk jugs and mixed containers, but the spot market prices indicated that there was no advantage for this type of sorting as prices are based on color and milk jugs come in a variety of colors. By collecting mixed HDPE plastic, the number of HDPE storage bins is reduced, making more room for other materials and potentially increasing the number of houses the vehicle can service.

After careful evaluation, the client was convinced to alter their original design decision; eliminating the requirement for distinct HDPE categories. The revised requirement states a more general need that HDPE must be processed and stored. It was determined that the time, space, and money required to process and store both white and clear HDPE separately was not justified by the minimal increase in price over mixed HDPE. The decision to eliminate the shredding requirement from the processing method had already been made previously when comparing baling and shredding, although baled HDPE showed the same pricing trend as regrind HDPE. Another reason behind the decision was the possibility of creating larger bales, which generally have greater resale value and may actually offset any cost increase that would have resulted from smaller color sorted bales.

Requirements have been successfully challenged with respect to identifying additional customers and their associated requirements (recycling companies and the associated material sales requirements) and tracing the requirements to their underlying design rationale (questioning the need for vacuuming). These two basic requirement challenging concepts, in addition to the physical testing concept discussed in Chapter 6, provides the basis for a method to question requirements.

CHAPTER 8

CONCLUSIONS

Challenging customer requirements on the EAI combined trash and recycling collection vehicle appears to have been a successful process based on the feedback from the industrial sponsor. Specifically, the design team was able to revise key requirements by applying the three concepts or principles for challenging requirements identified during the case study: physical testing (Chapter 6), defining more customers and refining their needs (Chapter 6 and Chapter 7), and tracing a requirement to its original design decision (Chapter 6 and Chapter 7).

Final Requirements

Multiple requirements were eliminated and revised as a result of challenging the initial customer requirements. In Table 8.1 the requirements that have been modified, added, or deleted are shown in the highlighted rows. The customers for each requirement, identified in the final column of Table 8.1, are defined in Table 8.2.

Table 8.1 – Final Requirements

No.	Description	Target Value	Target Unit	Justification/ Origination	Date Defined	Date Revised	Customer
1.	Must be capable of processing 350 households per day	350	H/D	EAI	9/6/05		1
2.	Must provide storage for 350 households per day	350	H/D	EAI	9/6/05		1

No.	Description	Target Value	Target Unit	Justification/ Origination	Date Defined	Date Revised	Customer
2.1	Must Separately store different categories of recyclables, plus trash	7	Recyclables	EAI	9/6/05	10/17/06	1, 3
2.2	Must accommodate Municipal Solid Waste (uncompacted)	8.0	yd^3	Pickens County	9/6/05	5/18/06	1, 2, 6
2.3	Must accommodate paper including newspaper and magazines (unbaled)	104	ft^3	EAI	9/6/05	5/18/06 10/17/06	1
2.4	Must accommodate PET plastic (unbaled)	63	ft^3	EAI	9/6/05	5/18/06 10/17/06	1
2.5	Must accommodate HDPE plastic (unbaled)	94	ft^3	EAI	9/6/05	5/18/06 10/17/06	1
2.6	Must accommodate clear glass (unbroken)	11	ft^3	EAI	9/6/05	5/18/06 10/17/06	1
2.7	Must accommodate cardboard and chipboard (unbaled)	106	ft^3	EAI	9/6/05	5/18/06 10/17/06	1
2.8	Must accommodate steel cans (uncrushed)	17	ft^3	EAI	9/6/05	5/18/06 10/17/06	1
2.9	Must accommodate aluminum cans (uncrushed)	15	ft^3	EAI	9/6/05	5/18/06 10/17/06	1
3.	Must process recyclables			EAI	9/6/05		1, 3
4.	Must compact trash			EAI	9/6/05		1, 2
5.	Must store processed recyclables			EAI	9/6/05		1, 3
~~6.~~	~~Recyclables must be removed by industrial vacuum~~			Note: Vacuuming is no longer required by EAI	9/6/05	10/17/06	1
~~6.1~~	~~Fluid must be removed from recyclables before vacuuming~~			Note: Vacuuming is no longer required by EAI	9/6/05	10/17/06	1, 3, 7
7.	Maximum unloaded vehicle weight	50,000	Lbs	EAI considerations / Federal Motorcar Safety Administration – Sec. 658.17	9/6/05		1, 7
8.	Maximum unloaded vehicle height	161	In	EAI	9/6/05		1, 7

No.	Description	Target Value	Target Unit	Justification/ Origination	Date Defined	Date Revised	Customer
9.	Maximum vehicle width	102	In	Federal Motorcar Safety Administration – Sec. 658.15	9/6/05		1, 7
10.	Must comply with all commercially operated vehicle rules and regulations			Federal and State Laws	9/6/05		7
10. 1	Must satisfy rear outboard seating position regulations			Federal Motorcar Safety Administration – S4.2, S4.3, S7.1	9/6/05		7
10. 2	Must meet operator work regulations			OSHA Regulations	9/6/05		7
10. 3	Must not exceed interior sound level at driver's seating position	90	Db	Federal Motorcar Safety Administration – Sec. 393.94	9/6/05		7
10. 4	Must not exceed maximum permissible sound level readings	See Figure	Db	Federal Motorcar Safety Administration – Sec. 325. **7**	9/6/05		7
10. 5	Must satisfy truck access requirements			Federal Motorcar Safety Administration – Sec. 399.207	9/6/05		7
11.	Requires standardized trash can for all households serviced			MSW side-loader requirements	9/6/05	10/17/06	1, 6

Table 8.2 – Final Customer List

	Customer	Justification
1	Environmental America Incorporated	Sponsor
2	Landfill Personnel	Receive and process waste
3	Recycling Facility Personnel	Receive and process recyclables
4	Vehicle operators – Driver, Recycler, MSW Collector	Operate vehicle for 8 hours a day
5	Vehicle servicemen	Perform maintenance and repair on vehicle
6	Household residents	Vehicle traverses their neighborhood/street and removes their trash/recyclables
7	Government – OSHA, FMCSA, DOT, NTSB	Subject to laws and regulations

The most significant requirement that was challenged was the solution based processing requirement. Where the initial customer requirements had statements such as "must shred", "must crush", and "must bale", the final requirements were revised to simply "must process recyclables". This was accomplished by applying all three concepts for challenging requirements. Testing proved that baling was a successful alternative processing method to shredding, while identifying the needs of recycling facilities revealed that baled recyclables were the preferred method of delivery. These findings enabled the customer to break the requirement down to its original design decision and make an informed choice to change the processing requirement to be solution independent.

Revising the requirement to process recyclables such that it was solution independent had a significant effect on other requirements. It enabled other solution dependent requirements such as "recyclables must be removed by industrial vacuum" and "fluid must be removed from recyclables before vacuuming" to be easily recognized and revised. In the case of the requirements related to industrial vacuuming, they were eliminated. However, that does not mean removing recyclables by way of industrial vacuum is not permitted. It is a possible design solution, yet not a requirement. In addition to eliminating the vacuuming requirements, revision of the processing requirement gave the client the ability to look at other requirements more objectively and revisit their original design decisions.

Revisiting the original design decisions behind requirements prompted the client to take a closer look at the mandated recyclable categories, specifically the highly specified categories such as glass and HDPE plastic. The price paid by recycling facilities for different categories of these recyclables was determined and compared to the expected material collection volumes. Ultimately, the client was able to evaluate recyclable material revenues, against collection volumes, processing requirements, sorting time, and vehicle size/weight. The result was less specific material categories. For HDPE, the categories of “clear HDPE” and “white HDPE” were simply replaced with “HDPE”. In the case of glass, based on extremely low collection volumes of brown and green glass relative to clear glass, the client made the decision to collect only “clear glass”. This revision was essentially a pragmatic business decision, but was exposed through the challenging of the initial requirements. The result of these requirement revisions was the reduction of the number of separate recyclable categories from eleven to seven.

Benefits of Challenging Requirements

The results of challenging requirements have been shown in this thesis to be positive. In the extreme case where no requirements are eventually changed, challenging requirements still results in a better understanding of the design problem. In the case of the EAI combined curbside collection vehicle, challenging requirements resulted in a clearer understanding of the design problem and a new requirements list which was more focused. Furthermore, the new requirements and the deeper understanding ultimately promoted the development of innovative solutions. It also helped to identify and address the needs of initial and additional customers.

Challenging requirements can help to clarify the design problem. By delving into the requirements and questioning those which appear erroneous, a designer gains a deep understanding of the underlying design problem. As each requirement is challenged, testing is conducted, customer needs are identified, and client decisions are revealed, the design requirements become clearer to all those involved. Too often in design, designers blindly accept requirements. This can result in wasted design effort and less than ideal solutions due to a lack of fundamental understanding of the design problem. Challenging requirements on the curbside collection vehicle resulted in a condensed and focused requirements list that was easily understood by both the designers and the client.

Ensuring that requirements are not solution dependent provides the designer with freedom to explore new ideas. Similarly, making sure that requirements are not overly constrained helps to promote flexibility in design. In the case of the curbside collection vehicle, removing the solution of "shredding" from the recyclables processing requirement enabled new designs to be considered such as the all-baler design presented in Chapter 5. This expands the available design space, thereby increasing the opportunity for achieving a better overall design solution. Furthermore, reducing the number of separately collected recyclables has many advantages: sorting time is reduced, material contamination is reduced, the number of processing systems is minimized, and the designer has more flexibility in terms of system packaging on board the vehicle. Ultimately, by challenging the requirements, the designers were able to operate with a simpler requirements list with greater design freedom. Thus, an open area of investigation in requirements definition is to develop and systematic, objective approach for defining which requirements are solution specific and which are independent.

One of the concepts identified for challenging requirements was identifying new customers and refining their needs. While it is often common practice to identify customers, it can be easy to overlook their needs and in some cases to miss identifying a customer altogether, as evidenced in this case study. Challenging requirements puts added emphasize on identifying customers and their needs as a key way of validating or refuting requirements. For example, the requirement to "shred" plastic was challenged based on testing which showed baling to be a feasible alternative. Baling was further supported by the identified need of the recycling facilities to receive the recycled material in bales as opposed to shredded, ultimately leading to the decision to revise the requirement. However, if the recycling facilities needs had been to receive the material shredded then the client may have decided to leave the requirement unchanged, preventing the cascade effect of requirement revisions explained previously in Chapter 7. Furthermore, if the needs of the recycling facility had gone unrecognized, the designers may have developed a solution that was unmarketable.

While the benefits of challenging requirements are many, no formal and systematic method currently exists for designers. In order for designers to realize the benefits of challenging requirements, a method must be developed that provides a structured process that can be applied to numerous different design problems.

Necessity for a Method to Challenge Requirements

The successful challenging of customer requirements in the EAI collection vehicle case study has proven the need for a method of challenging requirements. This method must help designers identify requirements to challenge and provide a systematic approach for challenging, while changing the culture of design to make questioning requirements acceptable. It must ultimately be accepted by both academia to train future engineers and industry to enable practicing professionals to improve their engineering efforts.

A method for challenging requirements must first help designers to identify requirements to challenge. The initial requirements for many design problems can be extensive and complex. Challenging all requirements would be time intensive and counterproductive to the successful completion of the project. Therefore, the method must provide a way to identify those requirements necessary of closer scrutiny. This may be possible by providing common guidelines for evaluating requirements such as, are requirements solution based, are requirements overly constraining the design space, or do requirements satisfy the needs of all customers. A list or database of guidelines for examining requirements could be provided as the starting point for this method.

Once requirements to challenge are identified, a systematic approach for challenging them is required. Many designers do not know how to formally go about challenging a requirement once they have identified one. Thus, this process must be a clear, step-by-step, procedure that can be adapted to different design problems regardless of the field or discipline [Pahl and Beitz, 1996]. It must arrive at requirement resolutions clearly and directly without relying on chance [Pahl and Beitz, 1996]. The EAI collection vehicle case study has identified three concepts for challenging requirements: physical testing, defining more customers and refining their needs, and tracing a requirement to its original design decision. These principles form a basis for the development of a systematic process. However, additional principles need to be determined through further case study investigation. Ultimately, each principal must have accompanying procedures that a designer can follow to challenge a requirement and reach a resolution.

Many designers are reluctant to question requirements due to educational training, company hierarchy, or society and culture. For example, from the author's own perspective, students are often taught that requirements are set-in-stone once they are defined and not subject to debate. In industry, an employee may be hesitant to question a requirement established by a superior due to office hierarchy. Similarly, a company representative may be cautious to question a client requirement for fear of damaging corporate relations. This is the culture in which designers find themselves and it is a culture that must evolve in an effort to improve design solutions.

Questioning and ultimately challenging customer requirements must become acceptable in academia, as well as industry. A formal method would help to make challenging requirements more common place and would be the first step towards making it acceptable. Ultimately, acceptance will come from good results, such as those observed in the EAI collection vehicle case study. Results could be shared in academia and industry, helping to show the benefits of challenging requirements, while allowing researchers, designers, and clients to learn from others experiences. This would promote ingenuity and understanding, as well as help the method to become easily taught and understood [Pahl and Beitz, 1996].

A database of requirements that have been successfully challenged may help clients to develop more focused requirements on future projects. This database could consist of the most common types of challenged requirements, such as solution dependent requirements, in addition to examples of requirements challenged in different industries or fields of research. It could combine typical solutions with their challenged requirements [Pahl and Beitz, 1996]. This could help clients to realize requirements problems more easily and early in the design process. Thus, clients could make some revisions without the need for more formal and time consuming testing and data acquisition. This could save time and money, while reducing workload, which Pahl and Beitz identify as one of the necessities of a design methodology.

The development of a formal method for challenging requirements could have a profound and lasting impact on engineering design. However, the success of the method depends on its ability to be adapted to different types of design problems and accepted by academia and industry. This thesis provides the foundation for the development of such a method.

LIST OF REFERENCES

Eliminate non-value added effort through lean manufacturing, Illinois Manufacturing Extension Center, 2005.

Environmental America INC. Business Plan, Environmental America Inc., November 16, 2004.

Focus on ICI, Saskatchewan Waste Reduction Council, *url*: http://www.saskwastereduction.ca/ICI/focus_on_ICI.htm, accessed October 20, 2005.

Lean Manufacturing, Iowa State University Facilities Planning and Management, 2005.

Lean Manufacturing Principles Guide-Version 0.5, University of Michigan, June 26, 2000.

Lean Manufacturing and the Environment: Research on Advanced Manufacturing Systems and the Environment and Recommendations for Leveraging Better Environmental Performance, U.S. Environmental Protection Agency, EPA100-R-03-005, October 2003.

Measuring Recycling: A Guide for State and Local Governments, U.S. Environmental Protection Agency, 1997, http://www.epa.gov/osw/conserve/tools/recmeas/docs/guide.pdf

Used Beverage Container Scrap Product Specifications, Alcoa Incorporated, 2004, http://beta.alcoa.com/rigid_packaging/en/pdf/UBC_Product_Spec_2004.pdf

Akao, Yoji (1994) "Development History of Quality Function Deployment", *The Customer Driven Approach to Quality Planning and Deployment*. Minato, Tokyo 107 Japan: Asian Productivity Organization, 339. ISBN 92-833-1121-3.

Anderson, David M. (1997) Agile Product Development for Mass Customization. McGraw-Hill Education – Europe.

Carreira, B. (2004) Lean Manufacturing That Works: Powerful Tools for Dramatically Reducing Waste and Maximizing Profits. New York, American Management Association.

C.-H. Chen et al. (2002) "A strategy for acquiring customer requirement patterns using laddering technique and ART2 neural network", Advanced Engineering Informatics 16 (2002) 229-240, Elsevier Science Ltd.

Cross, Nigel (1994) Engineering Design Methods – Strategies for Product Design. (2nd ed.) Chichester, Wiley and Sons Ltd.

Fu, M.W. and Lu, W.F. (2003) "Modeling and Management of Design Requirements in the Product Development Life Cycle", 2003 ASME Design Engineering Technical Conference and Computer Information Engineering Conference, Chicago, Illinois, USA, 2-6 September.

Garrett, Billy J. Jr. et al. "Waste Collection and Separation System," U.S. Patent 5,275,522, January 4, 1994.

Garrett, Billy J. Jr. et al. "Waste Collection and Separation System," U.S. Patent 5,511,687, April 30, 1996.

Garrett, Billy J. Jr. et al. "Recycling Vehicle," U.S. Patent 6,499,931 B1, December 31, 2002.

Gershenson, J.K. and L.A. Stauffer (1999). "A Taxonomy for Design Requirements from Corporate Customers." Journal of Research in Engineering Design, Volume 11, Number 2, pp.103-115.

Hazelrigg, George A. (1996) Systems Engineering: An Approach to Information-Based Design. New Jersey, Prentice Hall.

Howells et al. (To Recycling and Conservation Inc.), "Separated Discards Carrier," U.S. Patent 4,425,070, January 10, 1984.

Katrina, A. "The Basics of Lean Manufacturing & Maintenance."url: http://news.thomasnet.com/IMT/archives/2004/06/the_basics_of_l.html?t=archive accessed June 23, 2004.

Leposky, George. MRF Upgrades: A Tale of Three Cities. *MSW Management Journal*, September/October 2005.

Ohno, T. (1988) Toyota Production System. New York, Productivity Press.

Pahl, G. and W. Beitz (1996) Engineering Design: A Systematic Approach. (2nd ed.) New York, Springer-Verlag.

Peterson, Clint et al. (2007) "Product Innovation for Interdisciplinary Design Under Changing Requirements", 2007 International Conference on Engineering Design, Paris, France, 28-31 August.

Portney, Kent E. (1991) Siting Hazardous Waste Treatment Facilities: The NIMBY Syndrome. illustrated edition, Westport, CT, Auburn House

Pugh, S. (1991) Total Design, Integrated Methods for Successful Product Engineering, Addison Wesley.

Roberts, Edward B. (1989) "Strategic Transformation and the Success of High Technology Companies", MIT Sloan School of Management.

Suh P. Nam (1990) The Principles of Design. New York, Oxford University Press.

Suh P. Nam (2001) Axiomatic Design - Advances and Applications. New York, Oxford University Press.

Troy, T., Summers, J., (2006), "Augmenting "Pay As You Throw" with "Credit As You Recycle": Required Technology to Support Consumer Practice Change", AID

Technical Report, Department of Mechanical Engineering, Clemson University, Clemson, SC.

Ullman, David G. (1997) The Mechanical Design Process. (2nd ed.) New York, McGraw-Hill Companies.

Wiegers, Karl E. (2003) Software Requirements: Practical Techniques for Gathering and Managing Requirements Throughout the Product Development Cycle, Second Edition, Microsoft Press.

Young, Ralph R. *Effective Requirements Practices*. Boston: Addison-Wesley, 2001.

APPENDIX A – PET COMPACTING AND BALING TEST PROPOSAL

Generated - February, 26 2006

Objective:

To determine the PET bale densities and subsequent volume reduction that can be achieved with the vertical down-stroke baling system on the current EAI prototype truck. This data, along with published information, will be used to determine the ram face pressure necessary to achieve the minimum required bale density of 10 lb/cubic foot and asses the feasibility of baling PET plastic in this application.

Current Baling System Specifications:

- 6” bore hydraulic cylinder
- 24” stroke
- 1600psi regulated hydraulic line pressure
- Approx. 45,000lbs. of compacting force
- 30” x 28” ram face (Area=840 $in.^2$)
- Approx. 54psi ram face pressure
- 30” x 28” x 43” interior baler bin dimensions

Test 1:

- Create a half-bale of PET bottles without caps
- Bottles compacted after every 12-16” of bottles added to the bin
- Bale will be removed, measured, and weighed to determine its density
    - Bale dimensions:______________________________
    - Bale weight:____
    - Bale density: ____

Test 2:

- Create a half-bale of PET bottles without caps
- Bottles compacted when bin is completely full
- Bale will be removed, measured, and weighed to determine its density
    - Bale dimensions:______________________________
    - Bale weight:____
    - Bale density: ____

Test 3:

- Create a half-bale of mixed PET bottles (with and without caps)
- Bottles compacted after every 12-16” of bottles added to the bin
- Bale will be removed, measured, and weighed to determine its density
    - Bale dimensions:______________________________
    - Bale weight:____
    - Bale density: ____

APPENDIX B – PET COMPACTING AND BALING TEST

Generated – March 7, 2006

Objective:

To determine the PET bale densities and subsequent volume reduction that can be achieved with the vertical down-stroke baling system on the current EAI prototype truck. This data, along with published information, will be used to asses the feasibility of baling PET plastic in this application.

Current Baling System Specifications:

- 6” bore hydraulic cylinder
- 24” stroke
- 1600psi regulated hydraulic line pressure
- Approx. 45,000lbs. of compacting force
- 30” x 28” ram face (Area=840 in.^{2})
- Approx. 54psi ram face pressure
- 30” x 28” x 43” interior baler bin dimensions

Test Procedure:

1. Place a piece of cardboard (roughly 30” x 28”) at the bottom of the baler bin.
2. Remove the caps from all PET bottles entering the baler bin.
3. Fill the bin to the top with whole un-compacted PET bottles and assorted containers.
4. Position the hydraulic cylinder and ram over the bin.
5. Compact the PET plastic with one full down-stroke (24”) of the hydraulic cylinder. Note the hydraulic line pressure just before the cylinder reaches full stroke.
6. Hold compacted for 10 seconds and then raise baler ram.

7. Slide baler ram away from top of bin.
8. Record the distance between the PET plastic and the top of the bin.
9. Repeat steps 2-8 until the hydraulic cylinder is unable to complete a full stroke at the regulated pressure. This indicates that the maximum bale density of the system has been reached. Note the number of times the baler bin is filled and compacted.
10. Place a piece of cardboard (roughly 30” x 28”) on top of the PET plastic.
11. Insert each of the four baler tie straps through the individual channels.
12. Position the hydraulic cylinder and ram over the bin.
13. Compact the PET plastic to the fullest extent possible and hold.
14. Use a pair of pliers to pull the straps tight and tie each of them together.
15. Raise baler ram, open baler door, and operate the ejection strap to remove the bale.
16. Once bale is removed, record the dimensions and weight.

APPENDIX C – ALUMINUM COMPACTING AND BALING TEST

Generated – November 13, 2006

Objective:

To determine the aluminum bale density and subsequent volume reduction that can be achieved with the vertical down-stroke baling system on the current EAI prototype truck. This data, along with published information, will be used to determine if the system can meet or exceed the Alcoa minimum density requirement of 14 pounds per cubic foot..

Current Baling System Specifications:

- 6" bore hydraulic cylinder
- 24" stroke
- 1600psi regulated hydraulic line pressure
- Approx. 45,000lbs. of compacting force
- 30" x 28" ram face (Area=840 in.^{2})
- Approx. 54psi ram face pressure
- 30" x 28" x 43" interior baler bin dimensions

Test Procedure:

1. Obtain whole un-compacted aluminum cans and containers from recycling facility.
2. Fill the bin to the top with aluminum cans and assorted containers.
3. Position the hydraulic cylinder and ram over the bin.
4. Compact the aluminum with one full down-stroke (24") of the hydraulic cylinder.
5. Slide baler ram away from top of bin.

6. Repeat steps 2-5 until the hydraulic cylinder is unable to complete a full stroke at the regulated pressure. This indicates that the maximum bale density of the system has been reached.
7. Insert each of the four baler tie straps through the individual channels.
8. Use a pair of pliers to pull the straps tight and tie each of them together.
9. Open baler door and operate the ejection strap to remove the bale.
10. Once bale is removed, record the dimensions and weight.

APPENDIX D – EPA RECYCLABLE MATERIAL STANDARD VOLUME-TO-WEIGHT CONVERSION FACTORS

Category	Recyclable Materials (u/c – uncompacted/ compacted & baled)	Volume	Estimated Weight (in pounds)
FOOD SCRAPS[A]	Food scraps, solid and liquid fats	55-gal drum	412
GLASS	Bottles[B]:		
	Whole bottles	1 yd^3	500-700
	Semicrushed	1 yd^3	1,000-1,800
	Crushed (mechanically)	1 yd^3	1,800-2,700
	Uncrushed to manually broken	55-gal drum	300
	Refillable Whole Bottles[C]:		
	Refillable beer bottles	1 case = 24 bottles	10-14
	Refillable soft drink bottles	1 case = 24 bottles	12-22
	8 oz glass container	1 case = 24 bottles	12
LEAD-ACID BATTERIES	Car[D]	1 battery	39.4 lb
	Truck[E]	1 battery	53.3 lb lead and plastic
	Motorcycle[E]	1 battery	9.5 lb lead and plastic
METALS	Aluminum Cans[F]:		
	Whole	1 yd^3	50-75
	Compacted (manually)	1 yd^3	250-430
	Uncompacted	1 full grocery bag 1 case = 24 cans	1.5 0.9
	Ferrous (tin coated steel cans)[G]:		
	Whole	1 yd^3	150
	Flattened	1 yd^3	850
	Whole	1 case = 6 cans	22
	Major Appliances[E]:		
	Air conditioners (room)	1 unit	64.2
	Dishwashers	1 unit	92
	Dryers (clothes)	1 unit	130

Category	Recyclable Materials (u/c – uncompacted/ compacted & baled)	Volume	Estimated Weight (in pounds)
METALS (cont'd)	Freezers	1 unit	193
	Microwave ovens	1 unit	50
	Ranges	1 unit	181.1
	Refrigerators	1 unit	267
	Washers (clothes)	1 unit	177
	Water heaters	1 unit	131
PAPER	Newspaper[F]:		
	Uncompacted	1 yd^3	360-505
	Compacted/baled	1 yd^3	720-1,000
	12 in. stack	–	35
	Old Corrugated Containers[F]:		
	Uncompacted	1 yd^3	50-150 (300)[H]
	Compacted	1 yd^3	300-500
	Baled	1 yd^3	700-1,100
	Computer Paper[F]:		
	Uncompacted (stacked)	1 yd^3	655
	Compacted/baled	1 yd^3	1,310
	1 case	2,800 sheets	42
	White Ledger[F]:		
	Stacked (u/c)	1 yd^3	375-465/755-925
	Crumpled (u/c)	1 yd^3	110-205/325
	Ream of 20# bond; 8-1/2 in. x 11 in.	1 ream = 500 sheets	5
	Ream of 20# bond; 8-1/2 in. x 14 in.	1 ream = 500 sheets	6.4
	White ledger pads	1 case = 72 pads	38
	Tab Cards[F]:		
	Uncompacted	1 yd^3	605
	Compacted/baled	1 yd^3	1,215-1,350
	Miscellaneous Paper:		
	Yellow legal pads[F]	1 case = 72 pads	38
	Colored message pads[F]	1 carton = 144 pads	22
	Telephone directories[I]	1 yd^3	250
	Mixed Ledger/Office Paper[F]:		
	Flat (u/c)	1 yd^3	380/755
	Crumpled (u/c)	1 yd^3	110-205/610

Category	Recyclable Materials (u/c – uncompacted/ compacted & baled)	Volume	Estimated Weight (in pounds)
PLASTIC[J]	PET (Soda Bottles):		
	Whole bottles (uncompacted)	1 yd^3	30-40
	Whole bottles (compacted)	1 yd^3	515
	Whole bottles (uncompacted)	gaylord	40-53
	Baled	30 in. x 62 in.	500-550
	Granulated	semiload	30,000
	Granulated	gaylord	700-750
	8 bottles (2 L size)	16 L	1
	HDPE (Dairy):		
	Whole (uncompacted)	1 yd^3	24
	Whole (compacted)	1 yd^3	270
	Baled	32 in. x 60 in.	400-500
	HDPE (Mixed):		
	Baled	32 in. x 60 in.	900
	Granulated	gaylord	800-1,000
	Granulated	semiload	42,000
	Other Plastic:		
	Uncompacted	1 yd^3	50
	Compacted/baled	1 yd^3	400-700
	Mixed PET and HDPE (Dairy):		
	Whole (uncompacted)	1 yd^3	32
	Film:		
	Baled	semiload	44,000
	Baled	30 in. x 42 in. x 48 in.	1,100
TEXTILES[I]	Mixed textiles	1 yd^3	175
TIRES	Car Tires:		
	Whole tire[E]	1 tire	21
	Crumb rubber[K]	1 tire	12
	Truck Tires:		
	Whole tire[E]	1 tire	70
	Crumb rubber[K]	1 tire	60
WOOD	Wood chips[L]	1 yd^3	625
	Pallets[F]	–	30-100 (40 avg.)

Category	Recyclable Materials (u/c = uncompacted/ compacted & baled)	Volume	Estimated Weight (in pounds)
YARD TRIMMINGS[F]	Grass Clippings:		
	Uncompacted	1 yd^3	350-450
	Compacted	1 yd^3	550-1,500
	Leaves:		
	Uncompacted	1 yd^3	200-250
	Compacted	1 yd^3	300-450
	Vacuumed	1 yd^3	350
FURNISHINGS[E]	Foam rubber mattress	1 mattress	55
MUNICIPAL SOLID WASTE[M]	Residential waste (uncompacted at curb)	1 yd^3	150-300
	Commercial-industrial waste (uncompacted)	1 yd^3	300-600
	MSW (compacted in truck)	1 yd^3	500-1,000
	MSW (landfill density)	1 yd^3	750-1,250

Conversion Table Sources:

[A] Information obtained from Washington State.

[B] Draft National Recycling Coalition Measurement Standards and Reporting Guidelines presented to NRC membership. October 31, 1989.

[C] Personal communication with a representative from Allwaste. November 6, 1995.

[D] Battery Council International. 1995. 1994 National Recycling Rate Study.

[E] U.S. EPA. 1995. Methodology for Characterization of Municipal Solid Waste in the United States: 1994 Update. EPA 530-R-96-001. Washington, DC.

[F] U.S. EPA. 1993. Business Guide for Reducing Solid Waste. EPA530-K-92-004. Washington, DC.

[G] Personal communication with a representative from the Steel Recycling Institute. November 1, 1995.

[H] Information obtained from New Jersey and New York States.

[I] Information obtained from Massachusetts State.

[J] Personal communication with a representative from the American Plastics Council. November 2, 1995.

[K] Personal communication with a representative from the Scrap Tire Management Council. November 6, 1995.

[L] Information obtained from Northeast Forest Products, Martin Mulch Company, and the Solid Waste Association of North America.

[M] Solid Waste Association of North America, Manager of Landfill Operations Training and Certification Course. January 1989. Revised June 1991 and October 1994.

APPENDIX E – RECYCLING GLOSSARY

This is a glossary of terms as provided by *Recycler's World* (www.recycle.net). They are defined in the MarketPlace section under Spot Market Prices in each category.

Mixed Paper

Assorted paper of various grades or types of fibers. Bales shall be compressed into secure uniform bundles, not to exceed 72" in any dimension any with a minimum weight of 1,000 lb., Bale ties may be wire, strapping or appropriate bale cordage (unless otherwise declared by individual buyers).

Baled Corrugated Cardboard

Clean sorted printed or unprinted corrugated cardboard cartons, boxes or sheet, must be Kraft or jute liner content. May contain staples or poly tape, must be free of asphalt tapes and asphalt lined materials, may not contain more than 5% fiber re-enforced tapes.

HDPE Mixed Post-consumer Scrap (baled)

HDPE Mixed Post-consumer Scrap (baled) shall consist of assorted High Density Polyethylene (HDPE) bottle and container scrap compacted into secure bundles with a minimum weight density of 10 lb./cubic foot.

HDPE Mixed Post-consumer Regrind

HDPE Mixed Post-consumer Scrap (loose) shall consist of reground flake of assorted High Density Polyethylene (HDPE) bottle and container scrap.

Baled Mixed PET Scrap

Assorted PET bottles or containers compacted into secure bundles with a minimum weight density of 10 lb./cubic foot. May contain Post Consumer PET Soda Bottles of mixed colors.

Mixed PET Regrind

Colored PET Regrind shall consist of reground sorted colored PET bottles or containers

Used Beverage Cans (UBC loose)

Loose whole or flattened aluminum beverage cans, free from excessive dirt, liquid or other foreign materials. Equivalent to ISRI code TALAP or former code TALC.

Shredded UBC

Shredded UBC shall consist of aluminum Used Beverage Cans that have been magnetically separated and shredded into uniform material handleable (pneumatic) state. The shredded UBC shall have a minimum density of 12 lbs. (pounds) per cubic foot and a maximum weight density of 17 lbs. per cubic foot.

Must be fee of excessive fine material under 4 mesh in size. Must be free of other metals and foreign material. Equivalent to ISRI code TALCRED.

Baled UBC

Baled UBC shall consist of magnetically separated Used Beverage Cans that have been compressed into bales. Baled densities must be a minimum of 14 LBS. per cubic foot. Bale dimensions can range from 24" to 40" x 30" to 52" x 40" to 84". ISRI code TALDON shall be included in this grade

Mixed Steel Can Scrap

Flattened or whole steel cans. This material is typically generated from food cans from municipal recycling programs. May contain Bi-Metal (aluminum/steel) beverage cans. CAUTION May not contain aerosol cans.

Bundled Steel Can Scrap

Bundled Steel Can Scrap shall consist of compressed assorted flattened or whole steel cans with a minimum weight density of 75 lb./cubic foot. This material is typically generated from food cans from municipal recycling programs. May contain Bi-Metal (aluminum/steel) beverage cans. CAUTION May not contain aerosol cans.

Sorted Clear Container Glass

Sorted Clear Container Glass Scrap shall consist of clear, broken or whole container glass, (free of non-container glass, colored glass & foreign materials).

APPENDIX F – CLEMSON UNIVERSITY ME401 SPRING SEMESTER 2005
STUDENT DESIGN PROJECT

On-Truck Recycling System Design

Project Abstract:

Environment America Inc. (EAI) has developed a prototype trash/recycling collection system, investing in the fabrication of five demonstrator vehicles. EAI would like to design a series of independent modules for on-truck recycling. Your team is tasked with designing a module for:

- glass recycling (project 1)
- plastic recycling (project 2)
- metal recycling (project 3)
- paper recycling (project 4)

A clear problem definition with justification is required for approval by the customer. In order to accomplish this task, you will need to identify the recycling volume needs for a typical South Carolina trash/recycling pickup of 350 households. The volumes may be acquired from published governmental documents ("The State of Recycling in South Carolina"). Further, your team will need to specify how the recycled materials will be delivered to the final reclamation plant (cubed, shredded, ground, etc.). Finally, your team will need to design a modular recycling system that can be incorporated into a larger design. You will specify the system inputs, constraints placed upon your design, constraints generated by your design, operational costs, manufacturing costs, and avenues for future extensions to the design. This work will build upon the US Patent granted to EAI for the prototype system.

<u>Customer Contact:</u>

Joshua D. Summers, Assistant Professor of Mechanical Engineering

Chuck Kelley, Engineering Director for EAI

APPENDIX G – CLEMSON UNIVERSITY ME401 FALL SEMESTER 2005 STUDENT DESIGN PROJECT

On-Truck Recycling System Design

Project Abstract:

Environment America Inc. (EAI) has developed a prototype trash/recycling collection system, investing in the fabrication of five demonstrator vehicles. EAI would like to design a series of independent modules for on-truck recycling. Your team is tasked with designing an onboard baling module for the truck.

A clear problem definition with justification is required for approval by the customer. The baling system should be as small as possible, handle approximately 46 ft^3 of unbaled unsorted paper, 9 ft^3 of unbaled cardboard, use standard power and control systems, be safe to operate, and include storage on-truck as needed. The system should be as inexpensive to build, install, maintain, and operate as possible. Local recycling companies will be provided the baled paper (unsorted or sorted) and cardboard. A justification is required to determine whether it is economically feasible to combine paper and cardboard. While there are commercial off the shelf (COTS) systems available, these systems have limitations with respect to integration on the recycling/trash truck. Thus, custom baling systems may be required. Loading the balers will take place internal to the truck. Access to the internal work area on the truck is through openings between 3-5 ft wide.

The vehicle will be available for on-site inspection on October 4, 2005 behind EIB. Specific questions may be directed towards the CRITR development team:

- Dr. Joshua D. Summers (joshua.summers@ces.clemson.edu)
- Mr. Tim Troy (troy2@clemson.edu)
- Mr. Eddie Smith (ewsmith@clemson.edu)

You will specify the system inputs, constraints placed upon your design, constraints generated by your design, operational costs, manufacturing costs, and avenues for future extensions to the design. A complete drawing package, bill of materials, and assembly plan is required for this project. This work will build upon the US Patent granted to EAI for the prototype system.

Customer Contact:

Joshua D. Summers, Assistant Professor of Mechanical Engineering

Chuck Kelley, Engineering Director for EAI