SUSTAINABILITY STUDIES IN RECYLING

POST CONSUMER CARPET

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SUSTAINABILITY STUDIES IN RECYLING

POST CONSUMER CARPET

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"We could have saved the Earth but we were too damned cheap."

— Kurt Vonnegut, Jr.

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SUMMARY

This thesis presents some novel techniques to process Post Consumer Carpet waste and provides detailed cost comparisons between setting up and running small-scale decentralized units and large-scale centralized chemical facilities. The techniques presented include:

- A decentralized underlay manufacturing process which does not distinguish between the types of face fiber,
- A decentralized facility with twin screw extruder to depolymerize nylon 6 face fiber with a concurrent underlay manufacturing facility
- A decentralized pallet production facility, and
- A centralized facility for chemically depolymerizing nylon 6, and nylon 6,6 with a concurrent underlay manufacturing facility

The limiting factors to recycling are the collection of significant volumes of material and effective recycling techniques. This is illustrated in this study. The aim of this study is to enable recyclers to assess their recycling activities using various performance parameters, such as payback period of the venture, mass of carpet recycled, and energy used. Thus, this study aims to shed light on the impact of recycling on current carpet consumption per capita.

The results indicate that decentralized facilities located in metropolitan areas with populations of over 2 million people have a lower payback period than the large scale centralized facilities that are sparsely distributed throughout the country. These decentralized facilities are also more efficient in reducing the current carpet

consumption per capita. The reduced traveling distance for the post consumer carpet from the collection/disposal site to the processing facility should make a huge impact on energy consumption and the corresponding environmental emissions.

CHAPTER 1

INTRODUCTION

1.1 Context

Ask your carpet dealer if his or her company has access to a carpet recycling network, which is likeliest in California, says Bob Peoples, ex-executive director of the carpet industry's Carpet America Recovery Effort (CARE). You may strike out. Trouble is, there is no routine system for recycling old carpet, says Peoples [1]. The picture should begin to brighten by the end of 2007. "We're trying to build the infrastructure for collection around the country," says Paul Ashman, head of Environmental Recovery and Consolidation Services. "It's an industry that's just beginning." [2]

World fiber production has been steadily increasing in the past few decades as a result of population growth and higher overall living standards. In 2004, it exceeded 64 million tons [3]. The applications of fibers belong to one of three broad categories: apparel, home furnishings, and industrial. Most of fiber products are for short term (e.g. disposables) to medium term (e.g. carpet, apparel, automotive interior). The U.S. Environmental Protection Agency reports that in the United States alone, about 10 million tons of textile waste was generated in 2003 [4], accounting for 4.5% of the total municipal solid waste of 236 million tons per year. According to the same source, 55% of the municipal solid waste is landfilled, 14% is incinerated in waste-to-energy facilities, and 31% is recovered. Much of the fibrous waste is composed of synthetic and natural materials such as polypropylene, nylon, polyester and cotton.

The primary source of raw material for synthetic polymers is petroleum. Even processing of natural polymers such as cotton requires energy and the chemicals used are based on non-renewable sources [5].

The carpet industry in the United States produces 45% of all the carpet produced worldwide. It is a $12 billion industry at the mill level, producing almost 1.5 billion square meters of carpet products per year. In the United States the carpet market is split 70% residential and 30% commercial. Even though there exists vast diversity in types of face fibers, backing systems, additives and constructions, as a general rule of thumb, carpet weighs roughly 2.3 kilograms per square meter, which is 50% face fiber and 50% backing. The face fiber market is split resin-wise as follows: 40% nylon 6,6, 25% nylon 6, 25% polypropylene and 10% wool and other fibers [6].

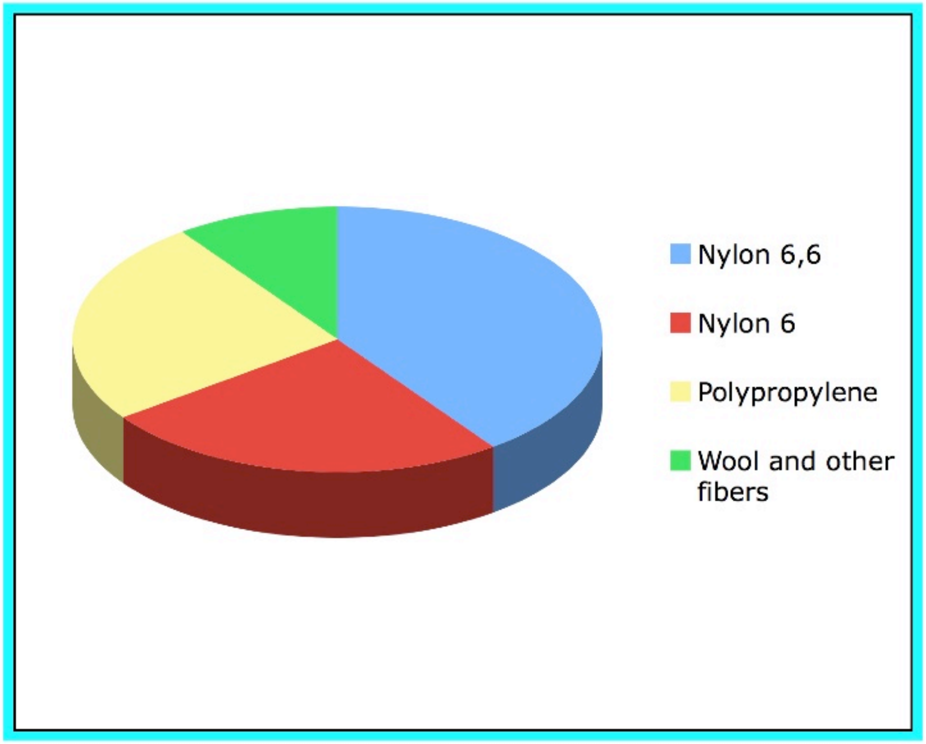

Figure 1.1: Split of carpet face fiber

Every year an estimated 5 billion pounds of post consumer carpet (PCC) is sent to the landfills in the USA. In 2006, a total of 261 million pounds of post-consumer carpet was reported to be diverted from landfill, with 240 million pounds being recycled. Carpet is a good source of fuel because of its high polymer content. Landfilled PCC corresponds to about 13 trillion BTU of energy [7]. The energy and raw material value embodied in this waste stream demands the development of technologies and markets for the recovery and re-use of such resources.

There are many compelling reasons for the recycling of waste carpet. They include conservation of resources, reduction of the need for landfills and paying the associated tipping fees, and provision of low-cost raw materials for products. In reality, the rate of carpet recycling is not very high. The attributed reason of insufficient public willingness to participate in recycling is often economics. Considering the complexities involved in the logistics of carpet collection and transport to the recycling facilities, the many collection schemes and recycling technologies should work in a concerted fashion to have an impact on waste carpet recycling.

1.1.1 Carpet Recycling: Early Efforts

Since nylon 6 and nylon 6,6 account for 65% of the face fiber used in carpet currently, much of the early efforts in recycling post consumer carpet focused on recovering nylon fiber by the fiber producers in the 1990s. In particular, BASF, Honeywell, and DSM focused on nylon 6, while Monsanto (now Solutia) and DuPont (now Invista) focused on nylon 6,6. These efforts resulted in patented technology for nylon depolymerization and dissolution for the recovery of pure monomers and polymer, which could be spun into carpet fiber or used in molding applications, either directly, or as a blend with virgin polymer. Though Monsanto and Dupont invested in pilot facilities, economic reasons and lack of interest in the marketplace led the plants to close down. Honeywell, along with DSM, invested in a large-scale nylon 6 depolymerization facility, Evergreen Nylon Recycling, in Augusta, GA. The plant was supposed to produce 100 million pounds per year of recovered caprolactam, the monomer of Nylon 6, derived from post consumer nylon 6 carpets, collected across the USA. The partners along with the state of Georgia invested $ 120 million in this venture [6]. Several problems, including but not limited to, drop in prices of virgin caprolactam prices in the worldwide market, engineering difficulties in the plant and lack of significant volume of carpet collected led the plant to shut down in August of 2001.

In the same period, Polyamid 2000, a carpet recycling facility was proposed to be in operation in Premnitz, Germany. $200 million dollars was pledged to this venture which included the old East German sector and was also designed to provide jobs in the region [6]. Carpet was to be collected from across Europe and shipped to Premnitz where it would be sorted by type. Nylon 6 was to be depolymerized to caprolactam, sold as monomer or repolymerized and sold as recovered post consumer nylon 6. Nylon 6,6 was to be mechanically sperarated and compounded into low-end resin for molding applications. Polypropylene was to be sold as resin as well. All other materials were to be sent to an on-site waste incineration facility to generate power and low pressure steam to be used in other parts of the plant. The focus was placed on covering operating costs and not on return on investment. Again, the logistics of collecting and shipping post consumer carpet across Europe proved challenging. European carpet is commonly a lower face weight product compared to U.S. carpet. So the yields of valuable face fiber per square meter were low. The plant even began importing carpet from the U.S to make up for the lost yield. However, poor economics associated with shipping carpet from the USA, low yields and no significant outlet for low grade nylon 6,6 resins led the plant to shut down in June of 2003.

Thus, the early efforts do not paint a pretty picture of the state of carpet recycling. Two major failures have been witnessed in the industry.

1.1.2 Carpet Recycling Technologies

Tufted carpet, the most common type (90%) as shown in Figure 2, typically consists of two layers of backing (mostly polypropylene fabrics) joined by calcium carbonate-filled styrene butadiene latex rubber (SBR). The face fibers (the majority being nylon 6 and nylon 6,6 textured yarns) are tufted into the primary backing [7]. The SBR adhesive is a thermoset material, which cannot be remelted or reshaped. The SBR waste typically goes back into the landfills.

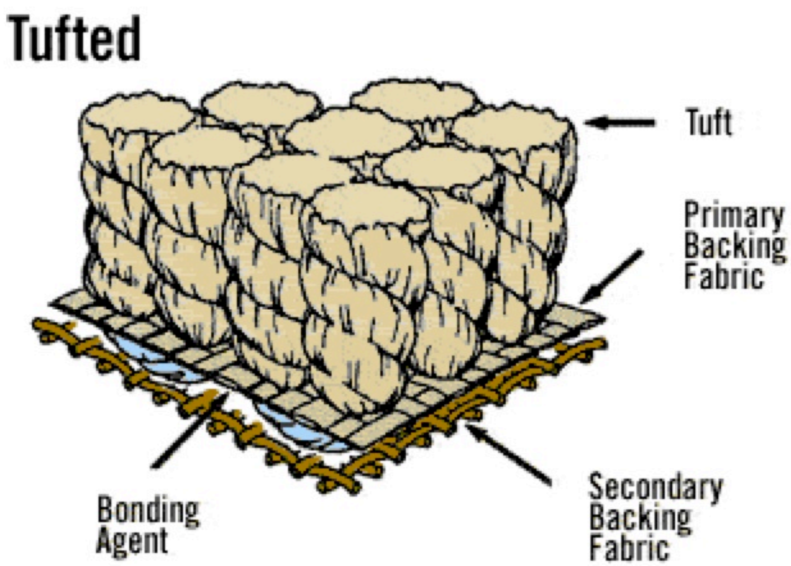

Figure 1.2: Illustration of Tufted Broadloom Carpet [56]

Recycling of polymers falls into one of the following four broad categories:

1) Primary recycling: Depolymerization to monomers (ie. nylon 6 to caprolactam and nylon 6,6 to hexamethylene diamine and adipic acid)

2) Secondary recycling: Recover individual components (Shred and granulate face fiber to make nylon pellets which can be reused)

3) Tertiary recycling: Melt blending the face fibers with other substances to enhance the resins properties.

4) Quaternary recycling: Incineration of waste carpet for energy recovery in cement kilns.

The relatively high fuel content of carpet polymers can reduce the need for other fuels and the calcium carbonate can serve as a raw material for cement [7].

The two recycling categories relevant to this project are primary and secondary recycling.

Primary recycling:

Depolymerization of nylon 6

Nylon 6 is made by polymerizing a single monomer, caprolactam. Chemical recycling of nylon 6 carpet face fibers has been developed into a closed-loop recycling process for waste nylon carpet. The recovered nylon 6 face fibers are sent to a depolymerization reactor and treated with superheated steam with or without a catalyst to produce a distillate containing caprolactam. The crude caprolactam is then distilled and repolymerized to form nylon 6, which is then spun and tufted again to form carpet.

Nylon 6 → Caprolactam

Depolymerization of nylon 6,6

This is more complicated than the previous case because nylon 6,6 is made of two monomers, hexa methylene diamine and adipic acid. Depolymerization of nylon 6,6 to recover HMDA and adipic acid have been demonstrated using steam hydrolysis with or without an acid/base catalyst but not commercialized yet.

Nylon 6,6 → HMDA + Adipic Acid

Secondary recycling

Size Reduction

Size reduction to cut large pieces of carpet into smaller sizes is achieved by mechanical means, like shredding. In a typical process, the feedstock is cut by a rotary drum fitted with hardened blades against a feeding bed, and the cut material is then moved against a screen with specified openings. The design for fibrous waste shredders requires sharp cutting edges and a tight gap between the cutting blades and the feeding bed to avoid fiber wrapping. High torque and low rotational speed for the cutting drum is preferred to avoid heating and melting the polymers [7].

Air separation of carpet components

Even though some of the backing will drop off in the shredding stage, most of the backing will have to be removed by an air separation system. Face fiber and the backing may be separated by means of an elutriator, which consists of a vertical tube up which air is passed at a controlled velocity. When the particles are introduced, often through a side tube, the smaller particles (face fiber) are carried over in the fluid stream while the large particles (backing) settle against the upward current.

1.1.3 Carpet Recycling: Current State

Carpet America Recovery Effort (CARE) is a joint industry-government effort to increase the amount of recycling and reuse of post-consumer carpet and reduce the amount of waste carpet going to landfills. CARE was established as a result of a Memorandum of Understanding, MOU, a national agreement signed by members of the carpet industry, representatives of government agencies at the federal, state and local levels, and non-governmental organizations [8].

The failed Evergreen Nylon Recycling plant was purchased by Shaw carpets, a subsidiary of Berkshire Hathaway, and is back in production as of June 2007. Some companies, like LA fiber in California, make carpet underlay out of recycled carpet. There are a few other recyclers out there who pelletize the face fiber and sell them.

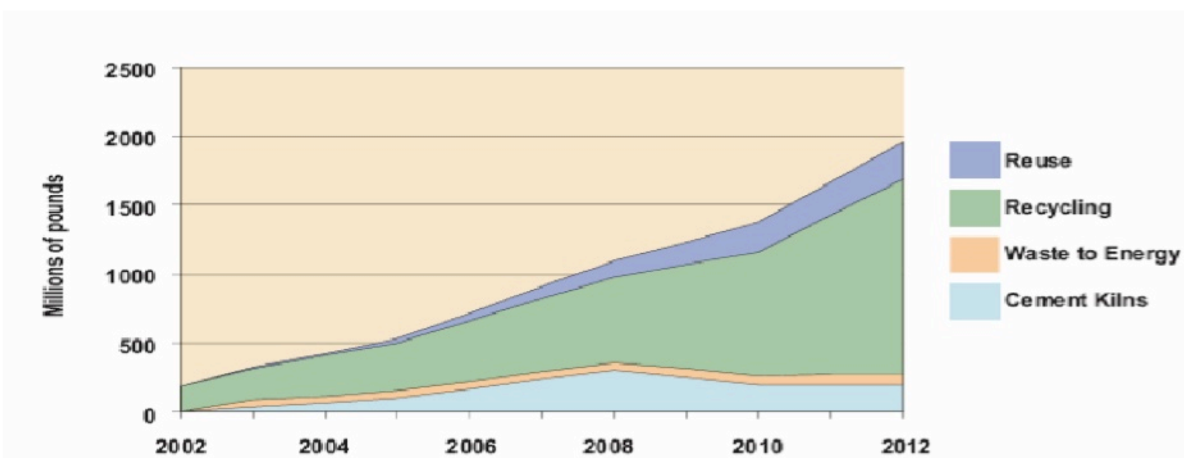

Figure 1.3: MOU Goals set by CARE over a ten year horizon [8]

1.2 Objective

The purpose of this thesis work is to demonstrate that successful carpet recycling companies can be set up, provided the collection scheme of post consumer waste carpet is successful. This project will evaluate the economic viability of creating a sustainable carpet recycling network for the markets of the future. The economics of this system are presented in order to be able to market this system. As a metric of success, the 'carpet footprint' of a person, which is the amount of carpet disposed in the US per capita, will be used.

CHAPTER 2

GOAL AND SCOPE DEFINITION

2.1 Goal

This thesis will present several techniques to process PCC waste and provide cost comparisons between setting up and running small-scale decentralized units and large scale centralized chemical facilities.

The techniques that will be presented include

(1) An underlay manufacturing process which does not distinguish between the types of face fiber,

(2) A twin screw extruder to depolymerize nylon 6 face fiber in multiple, distributed, small-scale facilities, and

(3) A large-scale facility for sorting nylon 6,6 and nylon 6 carpet by face fiber and then depolymerizing these nylons by catalytic hydrolysis, and

(4) A pallet production process which uses sorted nylon 6, nylon 6,6 and polypropylene face fibers.

The limiting factors to recycling remain the collection of significant volumes of material and effective recycling techniques. This will be illustrated in this study.

The aim of this study is to enable recyclers to assess their recycling activities using various performance parameters, such as economic viability of the venture, mass of carpet recycled and energy used. Thus, this study aims to shed light on the impact of recycling on the current amount of carpet disposed per capita.

The process capacities of the four techniques will be described. Material and energy balances will be presented. Equipment, capital and operating costs will be reported. The economic viability of these processing options will be discussed.

2.2 Scope of this study

For all three recycling strategies mentioned above, the energy utilized for a processing plant to run the equipment, the amount of material processed, and the manpower needed to operate the plant will be examined and their values will be compared.

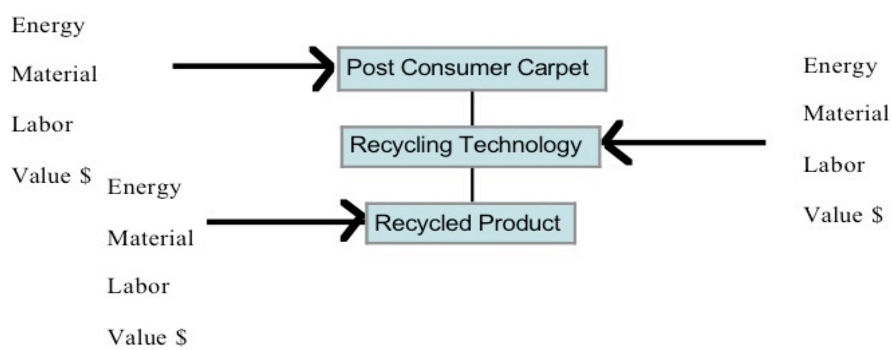

Figure 2.1 Scope diagram

CHAPTER 3

REVERSE LOGISTICS FRAMEWORK OF CARPET RECYCLING

The reverse logistics process of carpet recycling is flowcharted in figure 1 in order to understand the various components involved and their interrelationships in recycling post consumer carpet [6]. The understanding of the process will allow companies to make optimal cost-service trade-offs as well as help identify important cost drivers. Material quantities are important in order to make some reverse logistics programs viable. Dedicated redistribution and reclamation centers and recycling equipment require significant capital and these expenditures can be justified only if significant volumes are involved. If corporate stewardship or government take-back policies requires the suppliers to process the carpets at the end of life, then partnering with other companies, competitors and non-competitors, is an option. If not, outsourcing the reverse logistics to third parties is the best option.

For each case, data should be collected on the following:

What: the products entering the reverse logistics network and the products leaving the network, product-in and product-out

How: the main recovery processes used

Who: supplier of product-in, collector, processor, customer

Why: driving forces for the suppliers of product-in and initiator of the reverse logistics activities

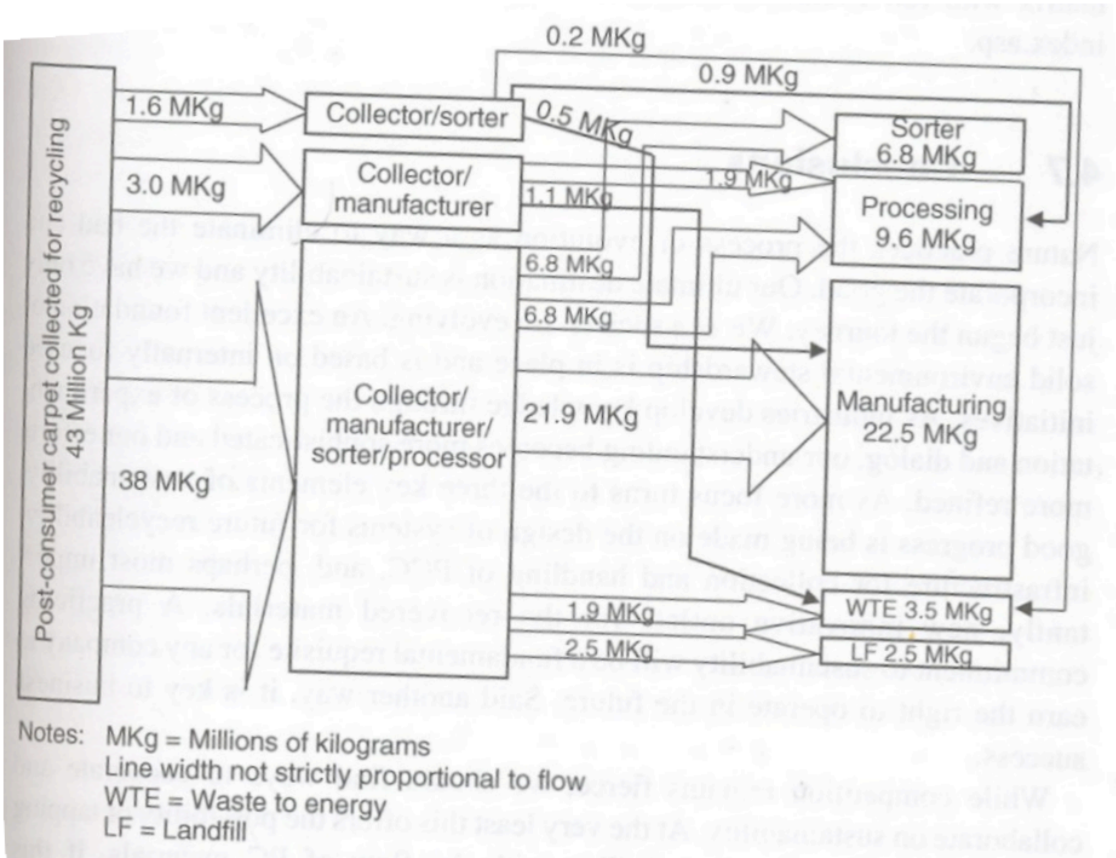

Figure 3.1: Reverse Logistics Framework of Carpet Recycling [6]

3.1 Goal and Scope Revisited

The costs involved in collecting post consumer carpet process has been studied previously by taking inventory of all the energy required, the material processed and the labor utilized [9].

3.1.1 Post Consumer Carpet Collection

The first task in recycling is collecting the post consumer carpet. Buildings with large quantities of discarded carpet, such as large commercial offices, are preferable targets for several reasons. First, the larger quantities of carpet available reduce the per unit hauling costs. The current tipping fee in Georgia is about $32.50 per ton or $0.015/lb [10]. The owner of the business should be willing to pay the recycler at least a portion of the transportation cost plus the tipping fee. Or if the owner brings the carpet himself to a drop off center, he should pay $0.015/lb in lieu of the tipping fee. The 50% backing in the carpet that is sent to the landfill will be covered in this amount.

Residential carpet has more face fiber than commercial carpet and hence is more attractive to recyclers. Compared with commercial installations, the quantity of residential carpet is lower. However, lack of strategically placed drop off centers makes it difficult to collect this carpet at present. In cities where residential carpet is collected with trash, most of the residential discard carpet would be sent to landfills. Recovering the carpet at the landfill is dirty, difficult, and dangerous (and usually requires a permit from the organization operating the landfill). If the recycler wants to collect carpet directly from the residence, the carpet installers should notify the recycler about the place and time when the discarded carpet would be removed during the installation of new carpet. This individual pickup would be the most expensive collection option.

3.1.2 Sorting

Distinguishing different face fiber types, particularly nylon 6 versus nylon 6,6, is difficult by visual inspection. Thus the recycler is likely to get all types of face fibers, not just the desired nylon. Equipment such as hand held infra red guns are available that can distinguish fiber types. The equipment costs about $18,000 - $22,000. Leasing options are available. After the collection and sorting stages, the carpet collected has incurred a cost of $0.06/lb [11].

3.2 Inventory Analysis

3.2.1 Broadloom Nylon Waste Carpet Estimates

Using the model from Guidry [9], the broadloom nylon carpet estimates are based on the country's population and estimates for pounds of carpet disposed per person. The percentage of nylon carpet from total broadloom carpet estimates is 65%, an industry wide estimate.

C	carpet estimate per person	17lb/person
P_i	population of country *i*	300 million
T	percentage of nylon carpet by weight	65%

$estimate = P_i * C * T$	**Equation 1**

3.2.2 Collection Scheme

The number of collection trips is determined by the truck capacity and product inventory estimates for each county in the different states. The truck capacity was determined by maximum load by weight of a 26' trailer with a gross vehicle weight (GVW) of 20,000lbs. The following equation represents the relationship between capacity and carpet estimates which determines the number of truckloads per county.

E_i	Broadloom Nylon Carpet estimate for county *i*	[lb]
C	truck capacity	7380 lb

$trips = \lceil E_i / C \rceil$	**Equation 2**

3.2.3 Transportation Emissions

The emissions statistics for the transportation process were obtained from relationships established by Govetto for Heavy Duty Diesel Vehicles (HDDV) with a gross vehicle weight range (GVWR) of approximately 5000-12,273 lbs [12]. Section 1 of Govetto's Appendix [12] includes a complete listing of fuel consumption rates and air emissions statistics for the HDDV used in this study traveling at an estimated rate of 55mph.

category	fuel consumption [L/km]	CO_2 emissions [g/km]	SO_2 emissions [g/km]
HDDV7-8	0.5	1150	0.42

3.2.4 Tipping Fees

For these calculations, the tipping fee for the state of Georgia, \$32.50/ton or \$.015/lb, is used as a national average tipping fee.

3.3 Summary

In this study, the transportation costs have not been taken into account for each of the four recycling scenarios. In order to have a comprehensive economic study done, the transportation costs for each recycling center should be considered.

CHAPTER 4

RECYCLING SCENARIO

4.1 Goal and Scope Revisited

The goal of modeling the recycling scenario for recycling post consumer carpet is to capture the economic impacts of such an end-of-life strategy. The scope of the recycling scenario includes estimating the labor, energy and material inputs for efficient collection of waste carpet, sorting them and sending them to the recycling facilities for further processing.

4.1.1 Depolymerization of Nylon 6

Nylon 6, a polymer made of caprolactam, is depolymerized into caprolactam in the extruder using a base catalyst such as KOH. Nylon 6 is depolymerized into caprolactam in a reactor using superheated steam and high pressure, with or without an acid (phosphoric acid) or base catalyst.

Nylon 6 → Caprolactam

4.1.2 Depolymerization of Nylon 6,6

Nylon 6,6, a polymer made of hexa methylene diamine and adipic acid, is depolymerized using either acid or base catalysed steam hydrolysis, breakdown of a chemical compound using water. Depolymerization of nylon 6,6 though studied in the laboratory has not been attempted on a large scale industrial level.

Nylon 6,6 → Hexa Methylene Diamine (HMD) + Adipic Acid

4.2 Recycling Techniques

4.2.1 Carpet Underlay

Post Consumer Carpet can be successfully converted to a non-woven carpet underlay, also called carpet cushion. It is known to provide a soft cushioned effect to those stepping on the carpet. In the absence of such padding, one walking on installed carpet would find the surface hard and unyielding. Non-woven carpet underlay is typically manufactured by putting small fibers together in the form of a sheet or web, and then binding them mechanically by interlocking them with serrated needles such that the inter-fiber friction results in a stronger fabric [13].

One problem encountered in laying carpet over traditional pads is that the carpet tends to stick to the pad during installation due to the frictional force between the two. One solution to this problem is to provide a loosely woven or non-woven pad to reduce the friction. Making carpet underlay from waste nylon would render the entire carpet installation more sustainable. Such a carpet underlay eliminates the need for hot melt seams. Hot melt seams are used to join two carpet pieces in an edge to edge relationship. While it provides a strong carpet joint along the adjacent edges, their major drawback is that a visible line is evident along the seam. It can also be felt by one walking across the carpet. The carpet tends to lift up at the seam because adhesion is not strong enough to keep the carpet firmly attached to the underlay [13].

In a commonly used method of installing carpet, the carpet is installed over a tackless strip secured to the floor around the walls of the room, the strip being provided with a series of protruding nails or tacks. The carpet is hooked onto the protruding nails of the strip on one side of the room and is then stretched before it is hooked up to the nails on the opposite side of the room. The carpet and any padding that may be beneath it has a tendency to wrinkle after the carpet has been subjected to traffic. It then becomes necessary to pull up the carpet, stretch it, trim it and fasten it again to the strip. Installation of such a tack-less strip is time consuming and presents a problem if the floor is not a wooden floor to which the strip is easily secured [13].

Gluing a conventional carpet underlay directly to the floor has some significant drawbacks as well. When applying the adhesive to the floor via a spray application, care must be taken to not coat the walls in the room being carpeted. In addition, the carpet underlay tends to absorb the adhesive and when the cushion is pulled away from the floor it tends to pull away with some portions tearing off and remaining adhered to the floor. After a period of time, the cushion also has a tendency to become substantially permanently compressed because of the absorbed adhesive, and most of the cushioning capability is lost. This failure of the cushion to rebound is called memory failure [13]. The carpet can also be stapled or nailed to the floor, but this will create dimples in the carpet and cushion, which would be noticeable to the person walking across the carpet [13].

Nylon fiber has good slip characteristics and excellent flame retardant properties. The carpet need not be glued to the underlay or tacked to it but simply lain over the underlay made of recycled waste nylon. Making carpet underlay from waste nylon carpet would render the entire system more sustainable. No adhesive would be needed to secure the actual carpet over the underlay because of the good slip characteristics of nylon. The carpet need not be color separated for recycling and the feedstock is not restricted to nylon carpets alone. Different types of face fiber can be webbed together.

4.2.2 Depolymerization of nylon carpets using an extruder

Recovering caprolactam from nylon 6 face fiber in PCC has been decentralized by using a counter rotating twin screw extruder. This extruder system renders a large scale chemical recycling facility unnecessary by replacing the system with something that can fit in a much smaller decentralized facility. This process falls under the primary recycling category.

Nylon 6, a polymer made of caprolactam, is depolymerized into caprolactam.

Nylon 6 → Caprolactam

Pyrolysis Method

Pyrolysis is the method of chemical decomposition of a substance in the absence of oxygen or any other reagents. Pyrolysis of nylon 6 at 800 deg C is said to produce caprolactam [14]. The thermal degradation of nylon 6 occurs over the temperature range 350-500 deg C. Loss of monomer randomly from within the polymer chain is a slower process than the backbiting from the ends of a restricted number of molecules which have labile ends, leading to sequential loss of monomer. The yield and purity of the monomer has not been reported [15].

Base catalysed pyrolysis method

The depolymerization of nylon 6 chips in a batch reactor was carried out by Mukherjee et. al. at low pressures (3-15 mm Hg) and elevated temperatures (225-270 deg C). The apparatus consists of a round bottom flask attached through an air condensor to another flask with vacuum applications. By increasing the catalyst concentration, the yield of caprolactam increased, started decreasing till it reached an asymptote. While increasing the temperature, from 225 to 240 deg C there is a gradual increase in yield and from 240 to 250 deg C the increase in yield is three-fold. Increasing the temperature from 250 to 270 deg C showed no appreciable increase in yield. The optimum conditions for the depolymerization were a temperature of 250°C, a pressure of 3 mm Hg, and a time 4 1/2 hr in the presence of 1% NaOH (w/w), which gave a 90.5% yield of caprolactam [16].

Bayer AG has patented a method in which they used potassium carbonate (0.5-2.5 wt %) as a catalyst to depolymerize nylon 6. In a stirred tank with an inert atmosphere and temperature range of 270-300°C, 95% of very pure caprolactam was recovered. It was also found that potassium carbonate increases the rate of depolymerization as compared to that of sodium carbonate. To receive the purity obtained, two distillations were done [17]. No reactions were done with non-nylon components present that might affect the purity of the product.

Catalytic pyrolysis of nylon 6 waste using α-alumina supported KOH (5% w/w) as the catalyst and a micro-scale reactor/molecular-beam mass-spectrometer system was carried out by Czernik et. al at NREL [18].The results were confirmed in a bench-scale fluidized bed. The reaction was carried out in an inert atmosphere and the caprolactam was trapped using a condenser, an electrostatic precipitator, a cold trap and a glass wool filter. At 330-360°C, the rate of the reaction and selectivity were high. In 60 minutes at 360°C, an 85% yield of caprolactam was obtained. The caprolactam collected was less than 90% pure and the major by-products were 2-ω-aminopentylazacyclohept-1- ene and a dimer of caprolactam [18].

To get dynamic measurements, Bockhorn et al. used a coupled thermogravimetry/ mass spectrometry, while to get isothermal measurements they used a closed loop-type reactor. To validate their results, a cycled spheres reactor was utilized. Under purge gas, it was found that the eutectic NaOH/KOH was the most efficient of the methods considered. With the eutectic NaOH/KOH, caprolactam with a purity above 99% was recovered at 290°C from a 5 hour run. Unfortunately, even though the rate increases at higher temperatures, undesired by-products are formed. It was found that water impeded the base catalyzed reaction [19,20].

Catalyst Determination Method

To determine the best catalysts that can be used to recover the nylon monomers from carpet, different base catalysts were mixed with pure nylons and then thermogravimetric analysis (TGA) was done to these samples [23].

Nylon 6 (Capron® 8200 NL-BPL) was obtained from Honeywell polymers before they were acquired by BASF. Nylon 6 post consumer carpet was provided by Wellman Inc. (Wellamid® N6 PCR). The bases considered were: potassium hydroxide (KOH), sodium hydroxide (NaOH), cesium hydroxide (CsOH), potassium carbonate (K2CO3), sodium carbonate (Na2CO3) and cesium carbonate (Cs2CO3); all of which was purchased from Fisher Scientific.

Since water impedes the base catalyzed reaction, the material needed to be dried before loading into the extruder. Prior to mixing, the nylon and catalyst were dried in a vacuum oven for 24 hours before weighing. For each sample, 30 grams of dried nylon mixed with a respective ratio of different catalysts. (For the initial screening, 3 grams of each base; i.e. 10 wt% of the nylon or 10:1 nylon to catalyst ratio was used.) Melt mixing of the nylon with the bases was done in a Haake® Rheomix 600 for 5 minutes under a nitrogen atmosphere at 240°C for nylon 6. The samples were removed promptly after mixing and allowed to air cool. After cooling, they were ground in a Standard Model No.3 Wiley Mill from Arthur H. Thomas Co. in Philadelphia using the 1 mm screen [23].

Comparative plots of the weight loss fraction versus temperature for each sample were then made using the TG to determine which catalyst(s) started and completed the degradation process fastest [23].

From TG measurements, it has been shown that both metallic hydroxides and carbonates decreased the onset degradation temperature of both nylon 6 and nylon 6,6. It was also determined that small amounts of these bases significantly lowered the onset degradation temperature when compared to the pure polymers. For some catalysts, degradation onset for 10:1 and 100:1 ratios of nylon to catalysts were around the same temperature. For N6, the most effective and the same time economical catalysts were KOH and K2CO3 [23].

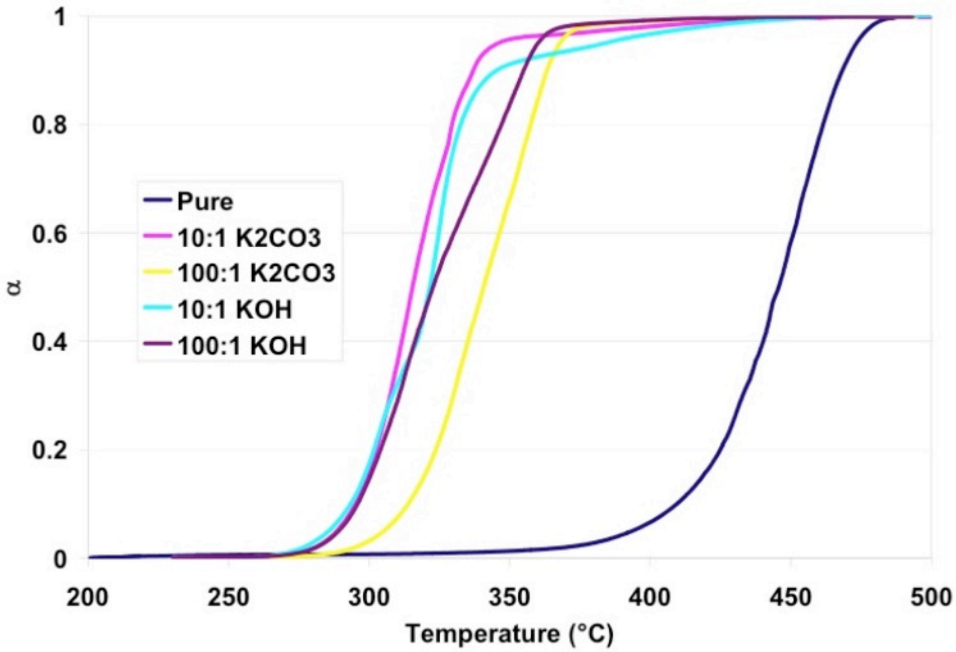

Figure 4.1 Comparison of 10:1 and 100:1 ratios of nylon 6 to KOH and K2CO3 catalysts [23]

4.2.3 Depolymerization of nylon carpets using hydrolysis

This section is based on a hypothetical situation in which both kinds of nylon face fiber are processed chemically to retrieve the respective monomers in a purified, reusable state. The capital costs for setting up such a chemical plant are so high that it makes it very difficult for small industry players to compete successfully. Also, the area of land needed for these facilities makes them centralized units. Hence, the transportation costs in bringing PCC from one part of the country to where the plant is located maybe sufficiently high. The Evergreen Nylon recycling plant in Augusta, GA, which belongs to Shaw Industries is the only chemical depolymerization facility. However, they only process nylon 6 fiber.

The case that has been studied comprises of a continuous, neutral hydrolytic depolymerization process of condensation polymers such as nylon 6 and nylon 6,6 [21]. The waste nylon is introduced into an aqueous hydrolytic zone at a temperature between 200 and 300 deg C and superatmospheric pressure of about 15 atm. High pressure steam is introduced into the lower portion of the hydrolysis zone underneath the level of the condensation polymer waste material. The steam serves as a principle source of heat for the hydrolysis zone. By being introduced underneath the level of the nylon, the steam agitates the waste material to provide heat transfer to accelerate the hydrolysis reaction. A portion of the steam condenses to provide water, a reactant in the hydrolysis reaction. An aqueous solution of the product(s) of the hydrolysis reaction is withdrawn from the upper portion of the hydrolysis zone.

A non-catalytic method is provided for depolymerizing nylon 6 has been patented [22]. The nylon, as a melt is continuously fed to a reaction zone together with superheated steam and undecomposed polymer melt is continuously withdrawn from the reaction zone together with steam and polymer decomposition products. Caprolactam is recovered from the polymer decomposition products. Caprolactam is hydrolytically cracked with from 1 to 20 parts by weight of water at a temperature between 250 and 300 deg C. The treatment is effected under super atmospheric pressure of 15 to 200 bar. The treatment is carried out with a residence time of 0.5 to 10 hours. The reaction mixture is then passed through a fluidized bed of alumina at a temperature of 250 to 400 deg C to obtain a mixture of steam and caprolactam. The product mixture comprises of caprolactam monomer, unreacted polycaprolactam and caprolactam oligomer which the monomer ranging from 1 to 70% by weight. The yield of caprolactam obtained was 97.3% when 300 g of nylon 6 and 1L of water was heated in a autoclave to 250 deg C at a pressure of 60 bar for 5 hours and then passed through a fluidized bed of alumina.

CHAPTER 5
UNDERLAY MANUFACTURING PROCESS

5.1 Goal and Scope Revisited

The economic viability of the carpet underlay manufacturing process will be studied by taking inventory of all the energy required, the material processed and the labor utilized.

5.1.1 Overview

The process diagram showing the preferred apparatus arrangement for manufacturing carpet underlay is shown in Figure 5.1

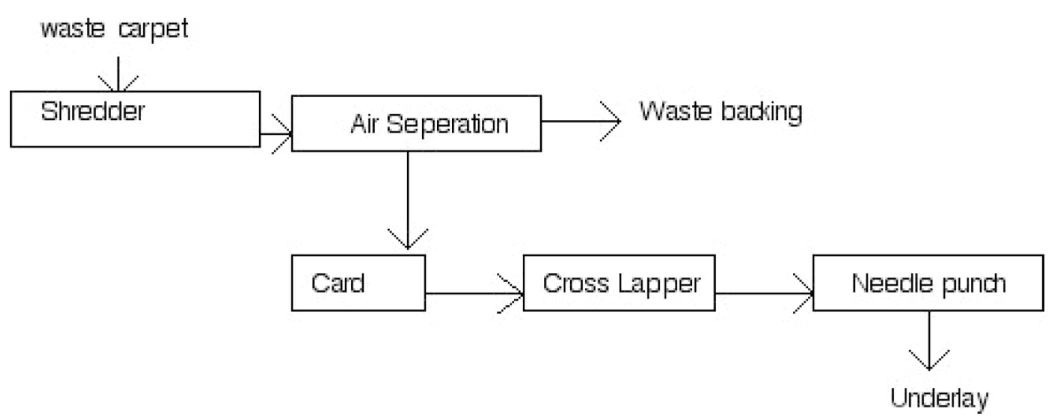

Figure 5.1 Carpet underlay manufacturing set up

The waste carpet carries 10% of its weight as dirt. This dirt and some of the backing falls off after the shredding process. As a general rule, 50% of carpet's weight accounts for the face fiber and the rest of it accounts for the backing. After the carpet has been shredded down to pieces ranging between 4 to 10 cm, it is sent through an air separator, which separates all the face fiber from the backing. These face fibers are then sent through the nonwoven underlay manufacturing equipment comprised of a card, a cross lapper and a needle punch. These three pieces of equipment constitute the fibrous web formation and web consolidation steps of the underlay manufacturing process. Even though commercially available cards may be incapable of effectively handling the short fibers that are obtained from waste carpet, special cards can be ordered from manufacturers for this specific purpose. Therefore, for the process to have a good pay back period, underlay comprising of a 90% yield by weight of the separated face fibers has been used for calculations.

5.1.2 Basis

The carpet underlay manufacturing facility uses all of the collected carpet in the manufacturing process. The facility is a decentralized one.

The amount of carpet disposed per year in the US is 2.3 billion kg. This corresponds to a disposal rate of approximately 7.6 kg/yr/person in the US. A city such as Atlanta has a population of about 5 million people and hence disposes 38 million kg of carpet every year. Assume about 30% of that carpet gets collected and shipped to the processing facility in that city. This corresponds to 11 million kg of carpet processed per year in such a facility. This facility runs 330 days a year for one shift of 8 hours per day with 3 operators/shift: one operator to run the shredder and air separation equipment, and two to run the dry web non-woven underlay manufacturing equipment. The three operators are also responsible for maintenance of the equipment and quality control of the underlay product. Hence, the amount of carpet processed here would be 4300 kg/hr if 11 million kg of carpet needed to be recycled per year. The calculations for this facility have been based on a round of number of 10,000 lb/hr or 4545 kg/hr of carpet being processed. This base amount is fairly close to the 4300 kg/hr calculated earlier, and hence is a reasonable estimate for the amount of carpet being collected and processed by such a decentralized facility.

The mass flow of the process is shown in Figure 5.2

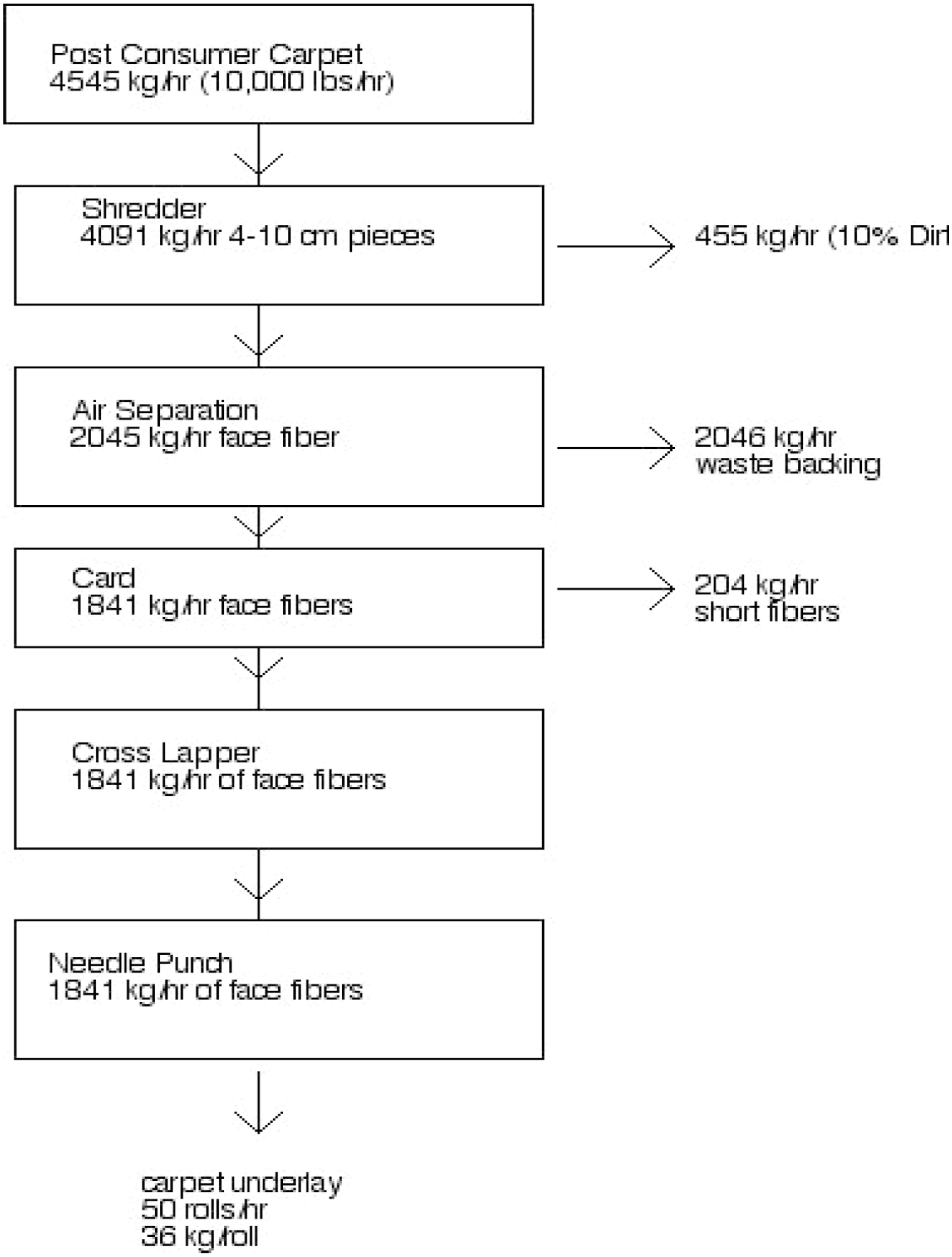

Figure 5.2 Mass flow diagram for the underlay manufacturing process

5.1.3 Equipment Description

Shredding:

Shredding reduces baled or unbaled carpet to fibrous material measuring preferably between 0.04 – 0.1 m. This is accomplished by passing the fibers through an effective screen size of about 0.05 m. This involves little removal of face fiber from backing. The shredder comprises of a high torque, low speed, high volume, single shaft with oppositely rotating grinding wheels which shreds the carpet into consistent, uniform small pieces, in a single pass. The technology utilizes a shearing principal which enables direct reduction of bulk material without the need for recirculation of the material for a particular sizing. In the equipment shown in Figure 5.3, the material is sheared as it is pinched between the revolving teeth and a stationary anvil. The shear's rotating members, rotor/hub, comprised of a number of teeth along the rotor's length, are so sized as to yield a desired particle size with a single pass through the anvil. This arrangement eliminates the need to classify and recycle material through the shredder. Shredders may be fitted with any number of screens which fit around the bottom half of the rotor. These screens provide further particle sizing and reduction since material cannot pass through the screen openings until it is properly sized. The shredder is outfitted with a hydraulic drive system. The hydraulic drive would then allow the shredder to have variable speed performance with the ability to absorb shock loads. A reject feature would allow unshreddable items to be ejected from the shredding chamber [24].

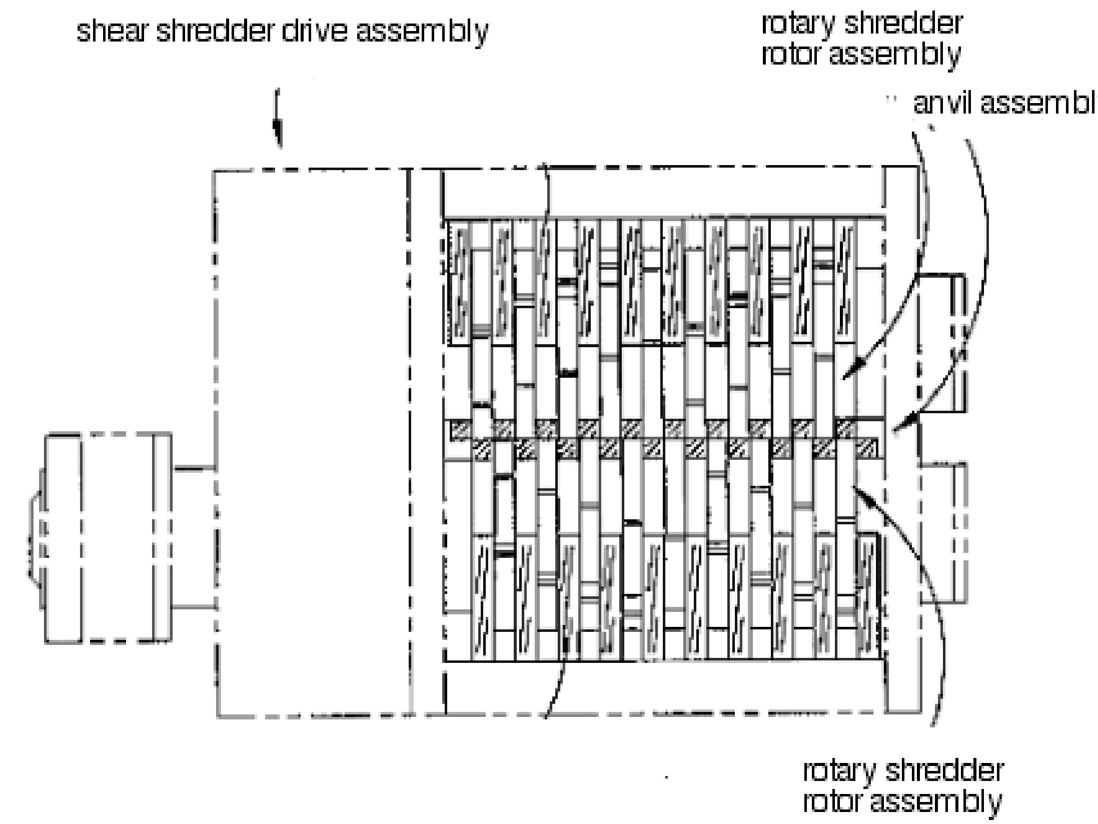

Figure 5.3: Cross-section of a shredder [24]

Air separation system

The air separation system serves to separate shredded material into a predominantly light fraction of carpet face fiber and a heavier fraction of backing material.

This is a centrifugal classifier comprised of a housing provided with inlets for material to be classified and classifying air and outlets for fines and for coarse material. It also has at least one rotor, which essentially consists of an annular series of blades and is mounted in the housing as shown in Figure 5.4. The rotor is mounted in the housing by at least one bearing, thus allowing it to be movable. The bearings must be lubricated and must be protected from the ingress of particles [25].

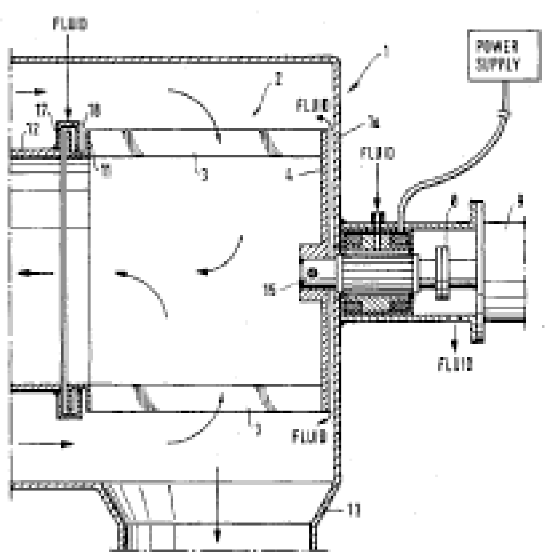

Figure 5.4 Cross section of a centrifugal air separation system [25]

Carding:

Carding serves to open and parallelize the fibers while removing fused fibers and chips of fibrous materials. The fibers being fed are pulled into the teeth of the flat-topped card-clothed roller. It is used to create mixes of different fibers, or different colors. It ensures that the fibers are thinned out and evenly distributed along a roll to facilitate spinning and layering as webs. [26]

Cards consist of two opposing rotary belts having opposingly bent wire teeth that separate and comb the fibers to form a thin web of straightened fibers. Flat fibrous webs from several cards are combined in a parallel or crosslaid manner to form the desired non-woven web weight and structure. These weak webs must be mechanically reinforced by needle punching or entanglement or chemically bonded by use of latexes or hot melts. The dry-laid web made by a card will have hooked ends when viewed microscopically as a result of the action of the bent wires on the card. [26]

The card is an excellent blending machine. Different types of face fibers are simultaneously introduced as a layered mat to the card entrance, the lickerin section in Figure 5.5. A uniform colored web is produced. The card however is also a high speed centrifugal system. This makes fibers of differing densities form layers throughout the thickness of the final web, and care must be used to avoid stratification when using blends of fibers have significantly different densities. [26]

Thus, the tangled mass of fibers fed to the machine is converted to a parallel sheet of well combed fibers by subjecting the fibers to a repetitive loosening-combing operation. In addition to loosening, combing and parallelizing the fibers, the rapid beating of the fibers causes a considerable quantity of impurities to fall out [27], [28].

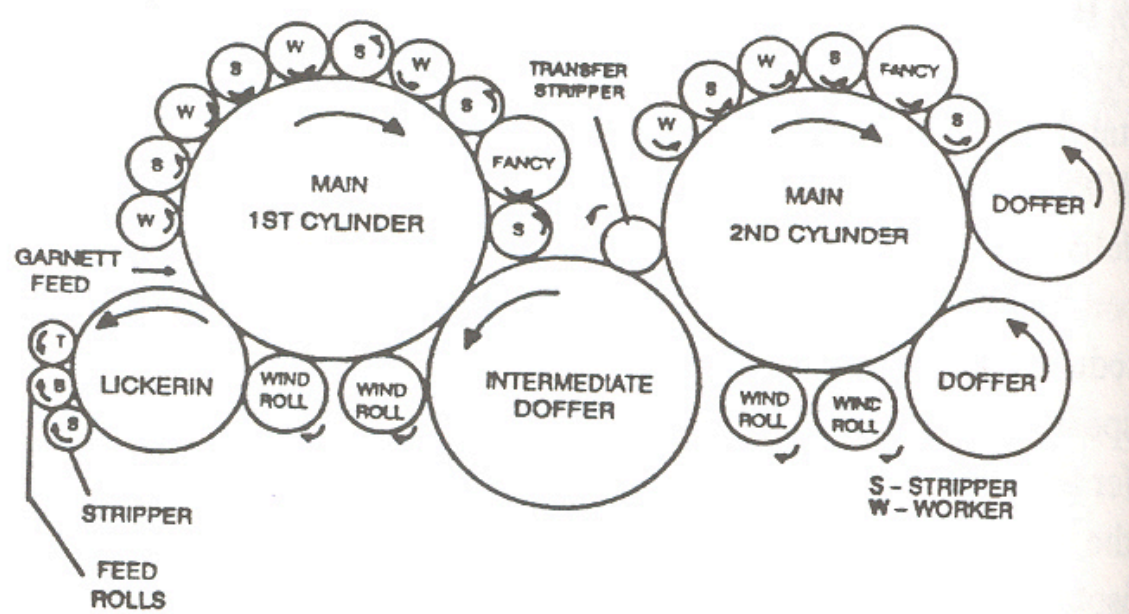

Figure 5.5 Cross section of a card [26]

Cross Lapping

The cross lapper is an apparatus for forming a layered, cross-woven web of predetermined width from a strip of webbed material. It is a method to get the desired width and web structure for the finished nonwoven underlay. It is accomplished by plating or folding webs that are formed on cards and delivered by a conveyor into the lapper, which continuously transfers the web onto an apron operating at right angles to the cross-layering motion as shown in Figure 5.6. The crosslapper can be adjusted to allow for width changes in the product line. With crosslapping, the heavy weights can be obtained simply by increasing the number of layers of webs from the card. The web is layered onto a floor apron that moves 90 deg from the input direction, thus the layers are biaxial. Scrim can be added for increased strength where two crosslappers are used in a line. [26]

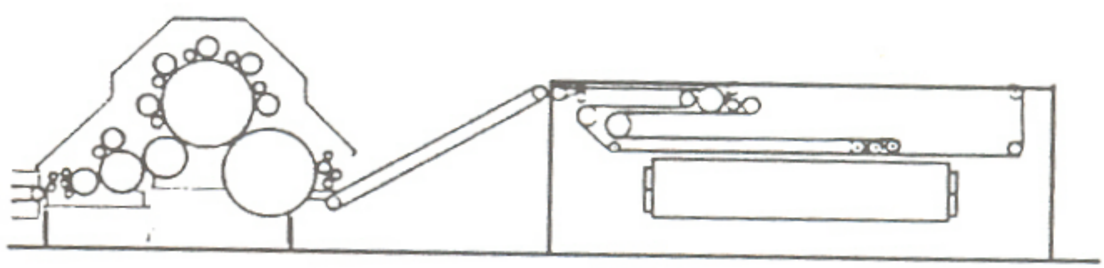

Figure 5.6 Cross section of a cross lapper [26]

Needle punch:

A needle punch is used to produce a compact sheet of tightly packed fibers with a thickness of about 1/4th to 1/2 of an inch. This is a process of bonding the nonwoven web structures by mechanically interlocking the fibers through the web. Barbed needles, mounted on a board, punch fibers into the web and withdraw the needles leaving the fibers entangled. The needles are spaced in a non-aligned arrangement and are designed to release the fiber as the board is withdrawn. By varying the stroke per minute, the advance rate of the web, and the degree of penetration of the needles, a wide range of fabric densities can be achieved. [26]

The apparatus shown in Figure 5.7 is capable of producing a needled fabric by needling the cross-lapped web of loosely matted fibers, a batt. The steps to do so are as follows:

- Advancing the web in a step-by-step motion through a confined throat,
- Initially penetrating the web from one side thereof by causing a first pattern of needles to travel in a path substantially perpendicular to the surface of the web while the web is moving
- Continuing penetration of the web by the first pattern of needles while the web is stationary to a point at least adjacent to its other side,
- Withdrawing the first pattern of needles while the web is stationary,

- Initially penetrating the web from the other side thereof by causing a second pattern of needles to travel in a path substantially perpendicular to the surface of the web while the web is moving and
- Continuing the penetration of the web by the second pattern of needles while the web is stationary to a point at least adjacent to the opposite side [29].

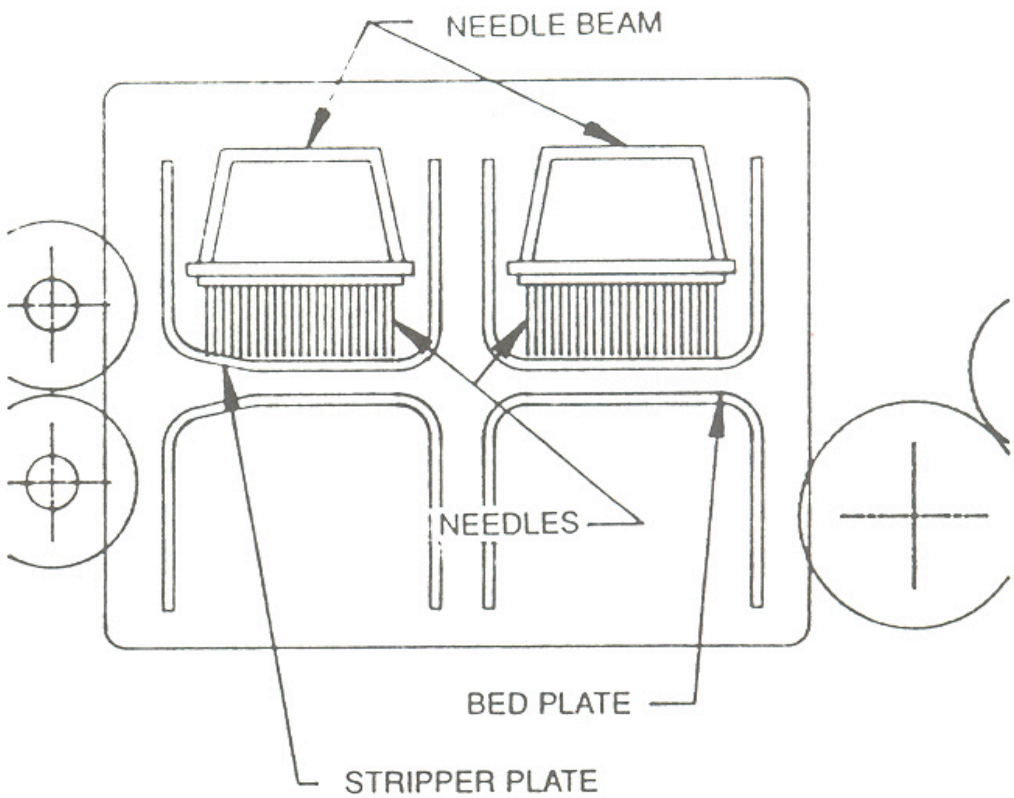

Figure 5.7 Cross section of a needle punch [26]

Each roll of underlay weighs about 36.4 kg. This allows production of 50 rolls per hour. They are sold commercially for about $2.64/kg. The length of the roll is 18 m and the width is 2 m [30].

5.2 Inventory Analysis

5.2.1 Mechanical Separation

Shredding: The shredder reduces unbaled carpet to fibers preferably between 4-10 cm using screens of about 5 cm. This involves little removal of face fiber from backing. The basis on which the estimate has been listed below for power usage depends on the material being processed. To process 4545 kg/hr, three shredders which process 1364 kg/hr each are used simultaneously in the facility. Detailed information is given in Appendix, A.

Equipment	Power Used (HP)	Material Capacity (kg/hr)	Cost (USD)
Shredder	300	1364	150,000

5.2.2 Air Separation System

Air separation system: The air separation system serves to separate granulated material into a predominantly light fraction of face fiber and a heavier fraction of backing material. The kind of agitator used is a closed vessel turbine which can withstand pressures to 150 psig. The equation for the purchase cost of the equipment is $2{,}850S^{0.57}$, where S is the motor HP. The range of allowed values for S are from 2-60 HP [31a]. The power in high velocity systems is given by $P = 1/2\rho v^3 AC_{d,}$ where ρ = 1.2 kg/m3 for air. Assume the velocity of a piece of carpet in the system v = 10 m/s, and radius of piece = 0.06 m. The drag coefficient, C_d, has been estimated from [35].

The mach number of particle = v_o/v_s = 10 m/s/343 m/s

This corresponds to C_d of 0.35 from [35].

P = 0.0024 kW = 0.003 HP / piece in the separator.

Number of pieces in the separator:

Density of carpet = 1825 kg/m^3 [36].

Volume of particle = 4/3 x pi x $R^3 = 9 \times 10^{-4}$ m^3

Amount of material processed in the air separator = 2045 kg/hr = 1.12 m^3/hr

Number of particles processed = 1245

Thus, power required to process 2045 kg/hr = 1245 x .003 HP = 4 HP

To get a higher fraction of light face fiber as opposed to heavier backing material, the power calculated above would be higher. Taking an efficiency factor of 0.5, the power required has been estimated to be 8 HP

Equipment	**Power Used (HP)**	**Material Capacity (kg/hr)**	**Cost (USD)**
Air Separator	8	2000	6,280

5.2.3 Card

Carding: Used to create mixes of different fibers, or different colors. It ensures that the fiber is thinned out and evenly distributed along a roll to facilitate spinning and layering as webs. The card that had been considered produces a web of 20 Deniers (amount of yarn per area of carpet) using fibers of length ~ 0.2 m. For this purpose of using short recycled fibers for underlay manufacture, special cards need to be ordered. For the purpose of carding about 2000 kg/hr of fibers, a carding machine with the following characteristics can be used [33].

Equipment	**Power Used (HP)**	**Material Capacity (kg/hr)**	**Cost (USD)**
Card	125	2000	800,000

5.2.4 Cross Lapper

Cross Lapper: Creates web of uniform thickness of about 0.01 to 0.02 m. For the purpose of carding about 2000 kg/hr of fibers, a crosslapper with the following characteristics can be used [33].

Equipment	Power Used (HP)	Material Capacity (kg/hr)	Cost (USD)
Cross Lapper	125	2000	600,000

5.2.5 Needle Punch

Needle punch: produces a compact sheet of tightly packed fibers with a thickness of about 0.02 m . The needle punch has 4 small needle boards with 6000 needles /m working width. For the purpose of carding about 2000 kg/hr of fibers, a needle punch with the following characteristics can be used [33].

Equipment	Power Used (HP)	Material Capacity (kg/hr)	Cost (USD)
Needle Punch	135	2000	1,600,000

The yield of this process is about 90% of the face fiber. Even though commercial equipment may not be suited for the purpose of carding, cross lapping and needle punching carpet fibers, customized equipment can be ordered for this purpose at these prices [33]. This is because some of the shredded fiber may to too short for carding.

5.3 Labor Requirements

The guidelines for estimating labor-related operations have been summarized in Seader, Seider and Lewin [8b]. Direct wages and benefits (DW&B) and other wages propotional to it are an important fraction of the cost of manufacture. Table 17.1 in [31b] lists labor related charges associated with operations.

Using a value of $30/operator-hr, the direct wages and benefits (DW&B) annually are calculated to be $30/operator-hr x 3 operators/shift x 1 shift x 8 hrs/day x 330 days/year, which is $ 237,600.

Operations related costs are as follows: direct salaries and benefits for supervisory and engineering personnel are 15% of DW&B and operating supplies and services are 6% of DW&B. In addition, $52,000/(operator/shift)-yr for technical assistance to manufacturing and $57,000/(operator/shift)-yr for control laboratory are added [31b].

Annual DW&B = $ 237,600

Using Table 17.1 in [31b], the other annual labor-related operations costs are

Direct Salaries and benefits for supervision = 0.15($ 237,600) = $ 35,640

Operating supplies and services = 0.06($ 237,600) = $ 14,260

Technical assistance to manufacturing = $52,000(2) = $ 104,000

Control laboratory = $57,000(1) = $ 57,000

A second category of labor costs is associated with maintenance of the processing plant. The equipment must be kept in working order, with repairs and replacement of parts made as needed. Maintenance wages and benefits are a fraction of the total depreciable capital. In the case of solids-fluids processing, according to [31b], it is 4.5% of C_{TDC} (Total depreciable capital). Salaries and benefits for engineers and supervisory personnel are 25% of MW&B (Maintenance wages and benefits), while maintenance overhead is 5% of MW&B. The total annual cost of maintenance runs at 8-11.5% of C_{TDC}.

C_{TDC} has been calculated using pieces of information from Table 16.9 in Seader, Seider and Lewin [31b]. These items are the cost of site preparation and service facilities, allocated costs for utility plants and related facilities, and cost for contingencies and contractor's fees.

Total cost of purchased equipment = $ 3,460,000

Equipment includes shredder, air separator, card, cross lapper, and needle punch.

Total bare-module cost for on-site equipment = $ 5,445,000, which is the sum of the bare-module costs of the process equipment.

The bare module cost is the product of the purchase cost of an equipment and its bare module factor, F_{BM}. A detailed list of all the F_{BM} values used for the above listed equipment is shown in Appendix C. The bare module factors, F_{BM} have been obtained from Guthrie [34] for various types of equipment. This factor takes into account the field materials for installation of the equipment, direct field labor charges, freight charges, contractor engineering expenses, and construction overhead.

Cost of site preparation and service facilities = cost of purchased equipment x 0.8 = $ 2,770,000.

Site preparation involves making land surveys, dewatering and drainage, surface clearing, addition of fencing, clearing of roads, sidewalks, and landscaping. Service facilities include maintenance shops; and laboratories for feed and product testing.

This value of 0.8 is a ratio factor used for estimating capital investment items based on delivered equipment cost. [32a]. The factors vary depending on the type of process plant being considered.

Cost of contingencies and contractor's fee = cost of purchased equipment x 0.52 = $ 1,800,000. This value of 0.52 is also a ratio factor based on delivered equipment cost [32a]. Contingencies are unanticipated costs incurred during the construction of a plant.

Using Table 17.1 in [31b], the other maintenance labor-related operations costs are

Total depreciable costs, C_{TDC} = $ 10,000,000

Maintenance wages and benefits (MW&B) at 5% of C_{TDC} = \$ 500,000

Salaries and benefits at 25% of MW&B = \$ 125,000

Materials and services at 100% of MW&B = \$ 500,000

Maintenance overhead at 5% of MW&B = \$ 25,000

5.4 Summary

The power required, the material processed and the labor utilized in the carpet underlay manufacturing process have been calculated in this chapter. The total power required to run the equipment is ~ 1290 HP. The amount of material processed by the facility is 4545 kg/hr of carpet. This produces a yield of 1840 kg/hr of carpet underlay. This facility runs 330 days a year for one shift of 8 hours per day with 3 operators/shift: one operator to run the shredder and air separation equipment, and two to run the dry web non-woven underlay manufacturing equipment. This facility will be compared with the other process that will be covered in later chapters. An economic viability study of all the recycling procedures will be presented in a later chapter.

CHAPTER 6

DEPOLYMERIZATION OF NYLON 6 USING AN EXTRUDER

6.1 Goal and Scope

The economic viability of the nylon 6 depolymerization via the extrusion process will be studied by taking inventory of all the energy required, the material processed and the labor utilized.

6.1.1 Overview

Nylon 6, a polymer made of caprolactam, is depolymerized into caprolactam in an extruder using a base catalyst such as KOH.

The process diagram showing the preferred apparatus arrangement for depolymerizing nylon 6 is shown below in Figure 6.1.

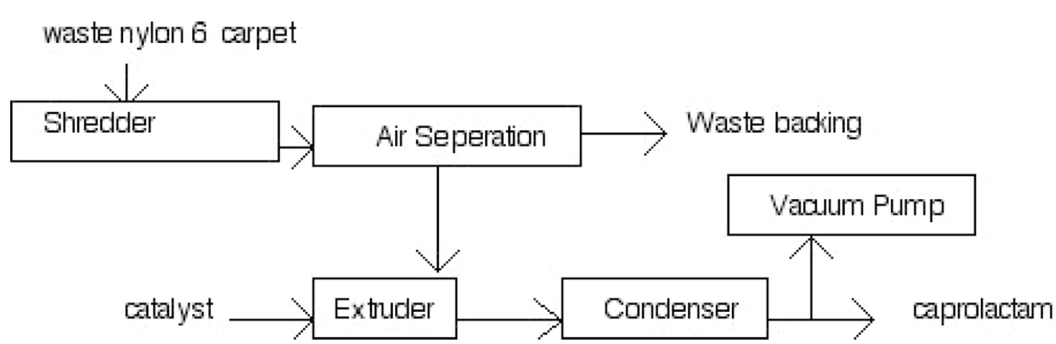

Figure 6.1 Extrusion set up for depolymerization of nylon 6

The above picture shows that waste carpet is sorted into nylon 6 carpet and carpet made of all other face fibers. This nylon 6 carpet is sent through a shredder to break it down into little pieces. These pieces are fed into a centrifugal air separator, which separates the heavier backing from the face fiber. The separated face fiber is then mixed with a catalyst and fed into an extruder, which in this case is used as a reactor. In this reactor under the right temperature the nylon fiber is broken down to its monomer, caprolactam. The caprolactam vapors are pulled out of the reactor system using a vacuum pump and condensed and collected. The caprolactam obtained this way needs to be further purified before it can be used to make nylon 6 again.

A mass balance for the above case is shown in Figure 6.2.

Basis : 10,000 lbs/hr of Post Consumer Carpet (PCC) processed

85% yield of caprolactam from reaction using nylon 6 and KOH catalyst has been reported by Czernik at NREL [18]. In 60 minutes at 360°C in a fluidized bed reactor, an 85% yield of caprolactam was obtained. The caprolactam collected was less than 90% pure.

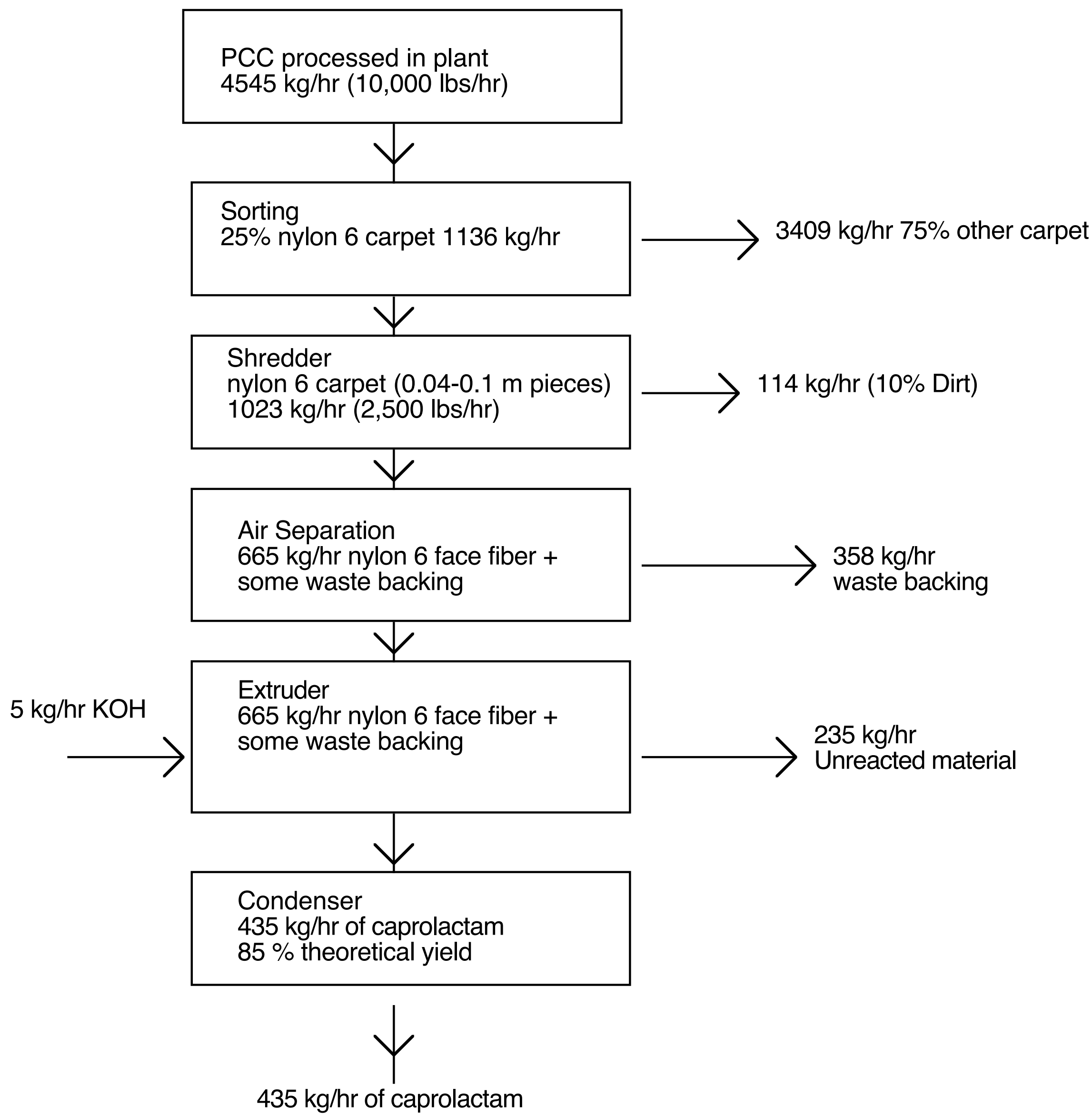

Figure 6.2 Mass flow diagram for waste nylon 6 carpet

6.1.2 Equipment Description

Extruder

The extruder can be considered as a back-mixed plug flow reactor. There are several economic advantages for using an extruder as a reactor, including: reductions

in real estate charges and the elimination of solvent purchases and recovery costs [23].

Some of the technical advantages of using an extruder include:

- superb dispersive and distributive mixing
- good temperature control
- control of the residence time distribution
- can attain high pressures
- provision to process continuously
- accessibility to and from different stages
- relatively easy removal of volatiles.

The extruder that is described here is a pilot scale extruder at Georgia Tech. It is used as the reactor for the depolymerization process. It is a 30mm counter rotating non-intermeshing twin screw extruder made by NFM Welding Engineers, Inc. and is shown in Figure 6.3. This extruder has three vents domes. Attached to the extruder vent domes is a vacuum collection system as shown in Figure 6.4. The reason for the vent collection system is to allow condensation of caprolactam vapors as they are formed in the reactor .

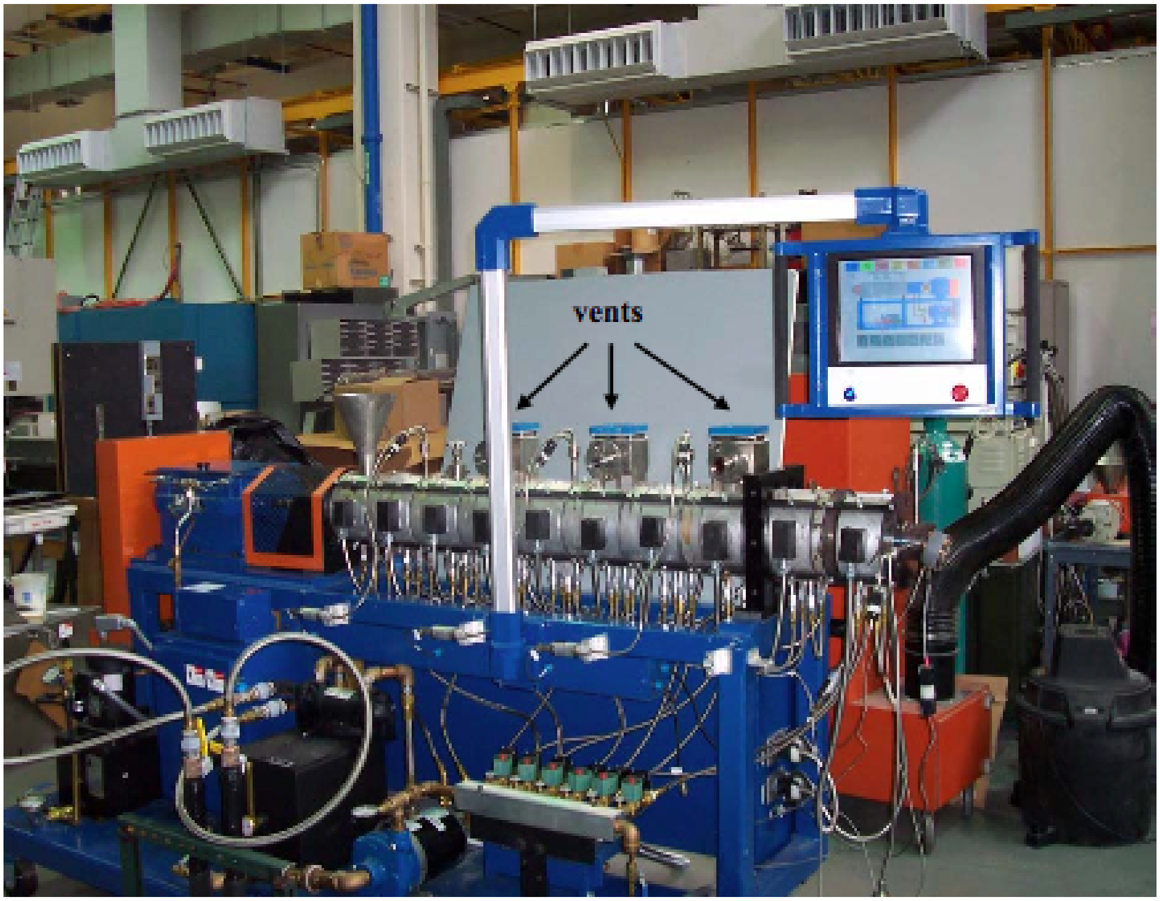

Figure 6.3 Extruder set-up in the lab for depolymerizing nylon 6 carpet. [23]

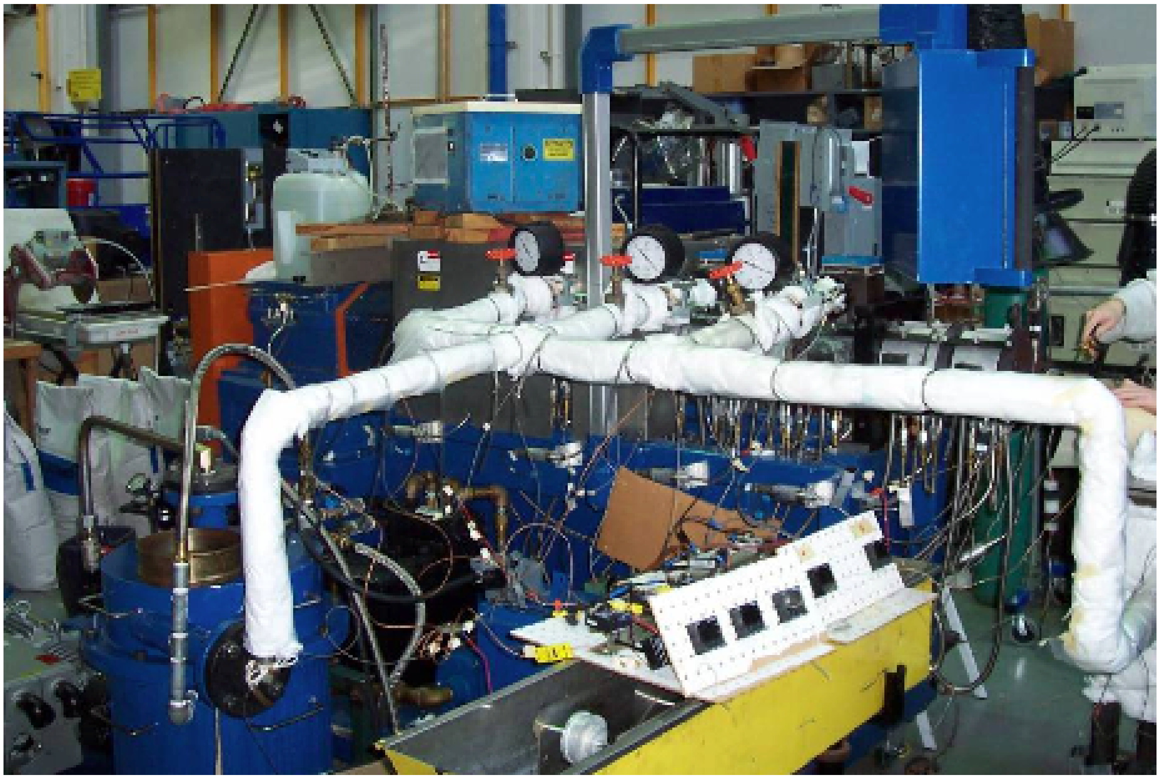

Figure 6.4 Vacuum system attached to the extruder [23]

The extruder is run with mixture of nylon 6 carpet and KOH, base catalyst in the ratio of 100:1 N6 carpet:KOH. As mentioned previously in chapter 4, from the TG measurements, it was determined that small amounts of these bases significantly lowered the onset degradation temperature when compared to the pure polymers. For KOH, the TG measurements showed that the degradation onset for 10:1 and 100:1 ratios of nylon to catalysts were around the same temperature. See Figure 4.1.

Based on laboratory runs by L. Bryson, the following temperatures are reasonable for running the extrusion process with nylon 6 waste carpet [23],

Melt zone and die temperature is preferably maintained at 250°C

Reaction zone temperature is preferably maintained between 375 to 400°C

The material throughput rate that was used in the laboratory is about 4.5 kg/hr.

The screw speed is 150 RPM

Vent lines temperature varies within the range of 250-300°C

Vacuum pressure varies within the range of -0.013 to -0.019 atm

Condenser

In systems involving heat transfer, a condenser is a heat exchanger which condenses a substance from its gaseous to its liquid state. In so doing, the latent heat is given up by the substance, and will transfer to the condenser coolant. For example a refrigerator uses a condenser to get rid of heat extracted from the interior of the unit to the outside air. Condensers are used in air conditioning, industrial chemical processes such as distillation, steam power plants and other heat-exchange systems. Use of cooling water or surrounding air as the coolant is common in many condensers.

A condenser using water as the coolant is attached to the line that emerges from the vents so that the caprolactam can be allowed to cool faster and condense in the collecting tank attached to the vacuum pump.

The condenser is designed in three stages. The temperature of caprolactam leaving the extruder is 350 deg C. The boiling point of caprolactam is 267 deg C.

Therefore, in the first stage, caprolactam is cooled from 350 deg C to 267 deg C. The heat required, $Q = m(Cp\Delta T + \Delta H_{vap})$, where Cp = 1.47 kJ/kg deg C, ΔH_{vap} = 574 kJ/kg, and m = 450 kg/h.

Q = 87 kJ/s = 87 kW

The coolant water enters at 30 deg C in the amount of 45,000 kg/h. The temperature to which it is rised is calculated as follows,

$\Delta T = Q/mCp$, where Cp = 4.187 kJ/(kg deg C) = 1.7

Therefore, water rises to a temperature of 31.7 deg C.

Heat transfer coefficient , $U = 0.36\ kW/m^2.K$, from table 14.5 of [32d]

Log Mean Temperature Difference, $LMTD = \Delta T_1 - \Delta T_2/\ln(\Delta T_1/\Delta T_2)$

LMTD = 20.9 K

Area of heat exchanger 1, $A_1 = Q/(U\ X\ LMTD) = 11.5\ m^2$

In the second stage, caprolactam is cooled from 267 deg C to 75 deg C.

The heat required, $Q = mCp\Delta T$, where Cp = 1.47 kJ/(kg deg C), and m = 450 kg/h.

Q = 35 kJ/s = 35 kW

The coolant water enters at 30 deg C in the amount of 45,000 kg/h. The temperature to which it is rised is calculated as follows,

$\Delta T = Q/mCp$, where Cp = 4.187 kJ/(kg deg C) = 0.7

Therefore, water rises to temperature of 30.7 deg C.

Heat transfer coefficient , $U = 0.56\ kW/m^2.K$, from Table 14.5 of [32d]

Log Mean Temperature Difference, $LMTD = (\Delta T_1 - \Delta T_2)/\ln(\Delta T_1/\Delta T_2)$

LMTD = 34 K

Area of heat exchanger 2, $A_2 = Q/(U\ X\ LMTD) = 1.8\ m^2$

Total area of the heat exchanger = $11.5\ m^2 + 1.8\ m^2 = 13.3\ m^2$

In the third stage, caprolactam is cooled from 75 deg C to 35 deg C. The solidification temperature of caprolactam is 70 deg C. To prevent it from solidifying in the tubes of the equipment, which would make retrieval very cumbersome, a steel conveyor belt has been added to allow the material to solidify and cool to room temperature.

The heat required, $Q = m(Cp\Delta T + \Delta H_{cond})$, where Cp = 1.47 kJ/(kg deg C), ΔH_{cond} = 138 kJ/kg, and m = 450 kg/h.

Q = 25 kJ/s = 25 kW

The amount of cooling water required is calculated thus, $m = Q/(Cp\Delta T)$, where Cp = 4.187 kJ/(kg deg C) and ΔT = (70 – 30) deg C = 40 deg C.

Therefore, mass flow rate of water required is 540 kg/h

Total cooling duty = 87 kW + 35 kW + 25 kW = 147 kW

6.1.3 Basis

The nylon 6 depolymerization facility only uses 25% of the collected carpet which is nylon 6 for the depolymerization using an extruder process. The rest, 75%, of the collected carpet, can be diverted to make carpet underlay. As shown in the previous chapter, the facility is also a decentralized one. The equipment costs, material and energy balances for such a facility has also been shown in chapter 5. Since both the underlay process and the extrusion process operate 330 days/year for one shift of 8 hours per day, no change in scale is required when incorporating the data from chapter 5 in this chapter.

The amount of carpet disposed per year in the US is 2.3 billion kg. This corresponds to a disposal rate of approximately 7.6 kg/yr/person in the USA. A metropolitan area such as Atlanta has a population of about 5 million people and hence disposes 38 million kg of carpet every year. Assume about 30% of that carpet gets collected and shipped to the processing facility in Atlanta. This corresponds to 11 million kg of carpet processed per year in such a facility. This facility runs 330 days a year for one shift of 8 hours per day with 6 operators/shift: one operator to run the shredder equipment, two for the extruder system, one for quality control, and two to run the dry web non-woven underlay manufacturing equipment. Hence, the amount of carpet processed here would be 4300 kg/hr if 11 million kg of carpet need to be recycled per year. The calculations for this facility have been based on a round of number of 10,000 lb/hr or 4545 kg/hr of carpet being processed. This base amount is fairly close to the 4300 kg/hr calculated earlier and hence is a reasonable estimate for the amount of carpet being collected and processed by such a decentralized facility.

6.2 Inventory Analysis

6.2.1 Mechanical Separation

Shredding: The shredder reduces unbaled carpet to fibers, preferably between 4-10 cm, using screens of about 5 cm. This involves little removal of face fiber from backing. The basis on which the estimate has been listed below for power usage depends on the material being processed. To process 4545 kg/hr of collected waste carpet, three shredders which process 1364 kg/hr each are used simultaneously in the facility. Detailed information is given in Appendix, A.

Equipment	**Power Used (HP)**	**Material Capacity (kg/hr)**	**Cost (USD)**
Shredder	300	1364	150,000

6.2.2 Air Separation System

Air separation system: The air separation system serves to separate granulated material into a predominantly light fraction of nylon face fiber and a heavier fraction of backing material. The kind of agitator used is a closed vessel turbine which can withstand pressures to 150 psig. The equation for the purchase cost of the equipment is $2{,}850S^{0.57}$, where S is the motor HP. The range of allowed values for S are from 2-60 HP [31a]. The power in high velocity systems is given by $P = 1/2\rho v^3 AC_{d,}$ where ρ = 1.2 kg/m3 for air. Assume the velocity of a piece of carpet in the system v = 10 m/s, and radius of piece = 0.06 m. The drag coefficient, C_d, has been estimated from [35].

The mach number of particle = v_o/v_s = 10 m/s/343 m/s

This corresponds to C_d of 0.35 from [35].

P = 0.0024 kW = 0.003 HP / piece in the separator.

Number of pieces in the separator:

Density of carpet = 1825 kg/m^3 [36].

Volume of particle = 4/3 x pi x R^3 = 9 x 10^{-4} m^3

Amount of material processed in the air separator = 2045 kg/hr = 1.12 m^3/hr. This amount corresponds to the amount of nylon 6 carpet that is depolymerized using the extruder and the rest of the collected carpet that goes through the underlay process.

Number of particles processed/hr = 1245

Thus, power required to process 2045 kg/hr = 1245 x .003 HP = 4 HP

To get a higher fraction of light face fiber as opposed to heavier backing material, the power calculated above would be higher. Taking an efficiency factor of 0.5, the power required has been estimated to be 8 HP

Equipment	**Power Used (HP)**	**Material Capacity (kg/hr)**	**Cost (USD)**
Air Separator	8	2045	8,760

6.2.3 Extruder

Extrusion: The nylon 6 carpet is heated to a molten state by a combination of heating elements and shear forces from the extrusion screws. The extruder is used effectively as a stirred reaction vessel where nylon 6 is broken down to caprolactam. The power usage and the cost of the equipment have been obtained from J.Muzzy [37].

Material processed (lb/hr) = 0.01 x (screw diameter in mm) $^{2.7}$ x (screw speed in RPM/500), where 500 is the max RPM

Power consumption (HP) = 0.15 x Material processed (lb/hr)

0.15 is an empirical factor that depends on material being processed.

Extruder cost ($) =1900 x (screw diameter in mm) $^{1.25}$

Equipment	Power Used (HP)	Material Capacity (kg/hr)	Cost (USD)
Extruder	227	680	520,000

6.2.4 Condenser

Condenser: A counter-current heat exchanger is used to condense the caprolactam vapors exiting the extruders. Cost of heat exchanger from Table 16.32 of [31a] = exp $\{7.8375+0.4343[\ln(A)]+0.03812[\ln(A)]^2\}$, where A ranges from 1-500 ft^2

Using an A = 143 ft^2 as previously calculated for the first and second stage of the condenser gives a cost = $ 55,800

For the third stage of the condenser a stainless steel conveyor belt that is 4 ft wide and 10 ft long that uses a 1HP motor drive is used to cool the caprolactam to 35 °C. The cost of this equipment would be $ 8,750. [38]

The total cooling duty required for cooling caprolactam from 350 °C to 35 °C has been calculated to be ~200 HP or 147 kW.

.

Equipment	Power Used (HP)	Material Capacity (kg/hr)	Cost (USD)
Condenser	200	450	63,750

6.2.5 Vacuum Pump

Vacuum pump: A reciprocating dry vacuum pump which has a an approximate vacuum level rating of 10-250 mm Hg would be suited for the purpose of pulling the caprolactam vapors from the reactor into the condensor. Based on the chart for purchase cost of reciprocating pumps given in Appendix, B, for suctioning 450 kg/hr of caprolactam or 10^{-4} m^3/s, the price of a stainless steel pump is ~ $1000 [32a]. For a reciprocating pump with a 2 m maximum head with a 70% efficiency rating, the pump would use 7.5 kW, which is about 10 HP [32b].

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Equipment	**Power Used (HP)**	**Material Capacity (kg/hr)**	**Cost (USD)**
Vacuum pump	10	450	1,300

The final caprolactam has a 85% yield of the face fiber based on reaction kinetics [18]. This yield is based on catalytic pyrolysis studies of nylon 6 waste using α-alumina supported KOH (5% w/w) as the catalyst carried out by Czernik et. al at NREL.

6.3 Labor Requirements

The guidelines for estimating labor-related operations have been summarized in Seader, Seider and Lewin [31b]. Direct wages and benefits (DW&B) and other wages propotional to it are an important fraction of the cost of manufacture. Table 17.1 in [31b] lists labor related charges associated with operations.

This facility runs 350 days a year for three shifts of 8 hours per day with 4 operators/shift, one operator to run the shredder equipment, two for the extruder system, and one for quality control. Using a value of $30/operator-hr, the direct wages and benefits (DW&B) annually are calculated to be $30/operator-hr x 4 operators/shift x 3 shifts x 8 hrs/day x 350 days/year, which is $ 1,008,000.

Operations related costs are as follows: direct salaries and benefits for supervisory and engineering personnel are 15% of DW&B and operating supplies and services are 6% of DW&B. In addition, $52,000/(operator/shift)-yr for technical assistance to manufacturing and $57,000/(operator/shift)-yr for control laboratory are added [31b].

Annual DW&B = $ 1,008,000

Using Table 17.1 in [31b], the other annual labor-related operations costs are

Direct Salaries and benefits for supervision = 0.15($1,008,000) = $ 151,200

Operating supplies and services = 0.06($1,008,000) = $ 60,480

Technical assistance to manufacturing = $52,000(2) = $ 104,000

Control laboratory = \$57,000(2) = \$ 114,000

A second category of labor costs is associated with maintenance of the processing plant. The equipment must be kept in working order, with repairs and replacement of parts made as needed. Maintenance wages and benefits are a fraction of the total depreciable capital. In the case of solids-fluids processing, according to [31b], it is 4.5% of C_{TDC} (Total depreciable capital). Salaries and benefits for engineers and supervisory personnel are 25% of MW&B (Maintenance wages and benefits), while maintenance overhead is 5% of MW&B. The total annual cost of maintenance runs at 8-11.5% of C_{TDC}.

C_{TDC} has been calculated using pieces of information from Table 16.9 in Seader, Seider and Lewin [31b]. These items are the cost of site preparation and service facilities, allocated costs for utility plants and related facilities, and cost for contingencies and contractor's fees.

Total cost of purchased equipment = \$ 4,000,000

Equipment includes shredder, air separator, extruder, condenser, stainless steel conveyor, card, cross lapper, and needle punch.

Total bare-module cost for on-site equipment = \$ 7,200,000, which is the sum of the bare-module costs of the process equipment.

The bare module cost is the product of the purchase cost of an equipment and its bare module factor, $F_{BM.}$ A detailed list of all the F_{BM} values used for the above listed equipment is shown in Appendix C. The bare module factors, F_{BM} have been obtained from Guthrie [34] for various types of equipment. This factor takes into account the field materials for installation of the equipment, direct field labor charges, freight charges, contractor engineering expenses, and construction overhead.

Cost of site preparation and service facilities = cost of purchased equipment x 0.8 = $ 900,000.

Site preparation involves making land surveys, dewatering and drainage, surface clearing, addition of fencing, clearing of roads, sidewalks, and landscaping. Service facilities include maintenance shops; and laboratories for feed and product testing.

This value of 0.8 is a ratio factor used for estimating capital investment items based on delivered equipment cost. [32a]. The factors vary depending on the type of process plant being considered.

Cost of contingencies and contractor's fee = cost of purchased equipment x 0.52 = $ 550,000. This value of 0.52 is also a ratio factor based on delivered equipment cost [32a]. Contingencies are unanticipated costs incurred during the construction of a plant.

Using Table 17.1 in [31b], the other maintenance labor-related operations costs are

Total depreciable costs, C_{TDC} = $ 8,600,000

Maintenance wages and benefits (MW&B) at 5% of C_{TDC} = \$ 430,000

Salaries and benefits at 25% of MW&B = \$ 107,000

Materials and services at 100% of MW&B = \$ 430,000

Maintenance overhead at 5% of MW&B = \$ 21,500

6.4 Summary

The power required, the material processed and the labor utilized in the nylon 6 depolymerization via the extrusion process have been calculated in this chapter. The total power required to run the equipment is ~ 1730 HP. The amount of material processed by the depolymerization facility is 1136 kg/hr of nylon 6 carpet. This produces a yield of 435 kg/hr of caprolactam. The amount of material processed by the underlay manufacturing facility is 3409 kg/hr of non nylon 6 waste carpet. This produces a yield of 1530 kg/hr of carpet underlay. This facility runs 330 days a year for one shift of 8 hours per day with 6 operators/shift: one operator to run the shredder equipment, two for the extruder system, one for quality control, and two to run the dry web non-woven underlay manufacturing equipment. The facility that has concurrent procedures of nylon 6 depolymerization and underlay manufacturing will be compared with the other processes presented. An economic viability study of all the recycling procedures will be presented in a later chapter.

CHAPTER 7

DEPOLYMERIZATION OF WASTE NYLON IN A CENTRALIZED FACILITY

7.1 Goal and Scope Revisited

The economic viability of a neutral, hydrolytic depolymerization process of nylon 6 and nylon 6,6 will be studied by taking inventory of all the energy required, the material processed and the labor utilized.

7.1.1 Overview

The case that will be studied consists of a continuous, neutral hydrolytic depolymerization process of condensation polymers, such as nylon 6 and nylon 6,6. This process has been described in chapter 4.

In the case of nylon 6 carpet, only one product is formed which is caprolactam. The oligomers that are produced during the hydrolysis reaction are recovered and recycled to the hydrolyzer. [21]

The process diagram showing the preferred apparatus arrangement for depolymerizing nylon 6 is shown below in Figure 7.1

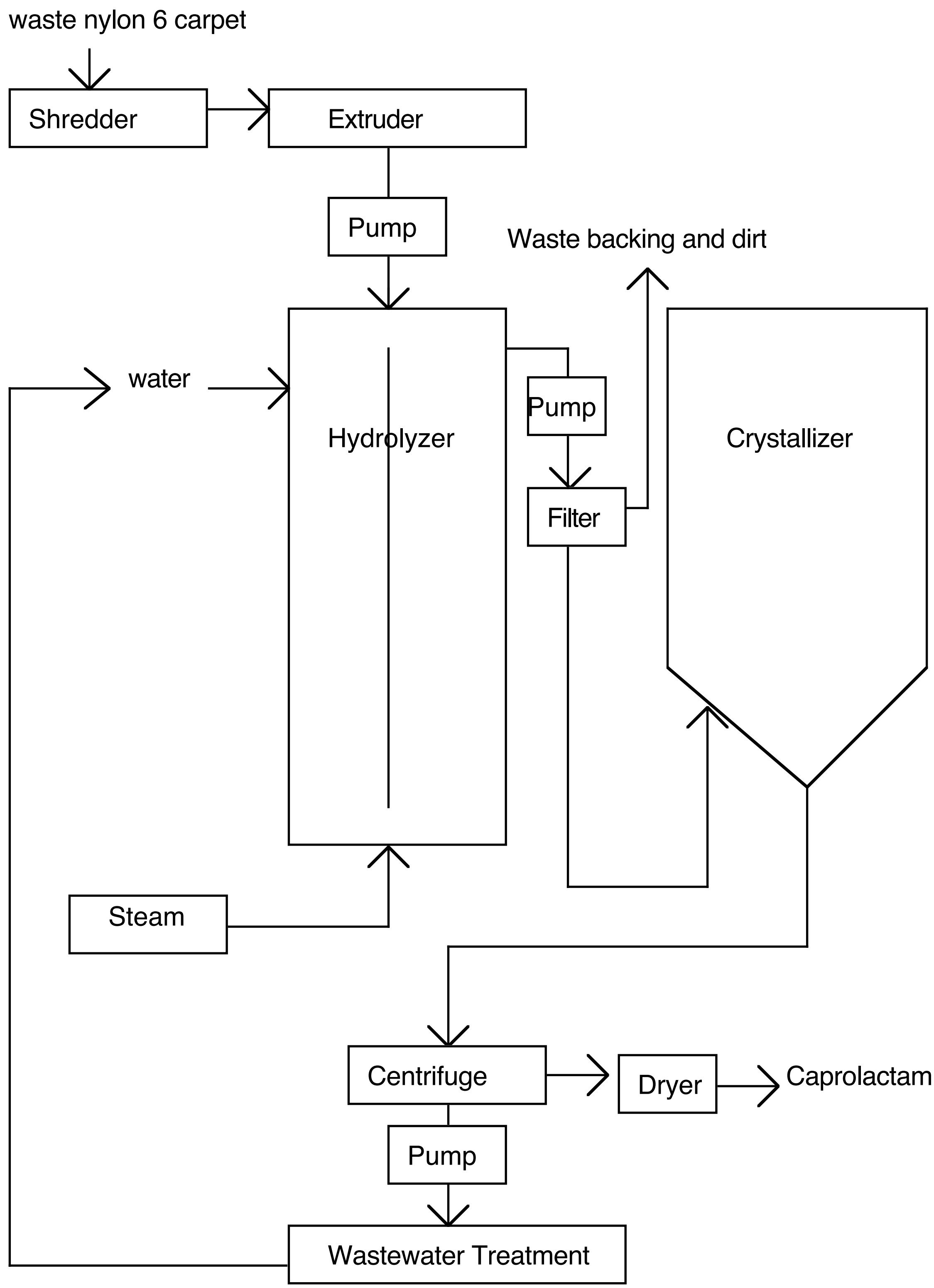

Figure 7.1 Hydrolysis reaction set up for depolymerization of nylon 6

The waste carpet is sorted into nylon 6 carpet and carpet made of all other face fibers. This nylon 6 carpet is sent through a shredder to break it down into little pieces. These pieces are fed into an extruder, which transfers the face fiber into a vertical cylinder hydrolyzer where the depolymerization occurs. In this reactor under the right temperature the nylon fiber is broken down to its monomer, caprolactam. The material is then sent to a filter where the backing and dirt are separated from the reacted material. A continuous crystallizer, made up of a vertical tank and a conical bottom is connected to the filter to collect the dissolved caprolactam. A continuous centrifuge receives the discharge from the crystallizer and sends it to the drier [21].

A mass balance for the above case is shown in Figure 6.2

Basis : 10,000 lbs/hr or 4545.45 kg/hr of Post Consumer Carpet (PCC) processed

Based on reports of depolymerization reactions as listed in Chapter 4, an average yield of 80% of caprolactam from reaction using nylon 6 has been used for calculations.

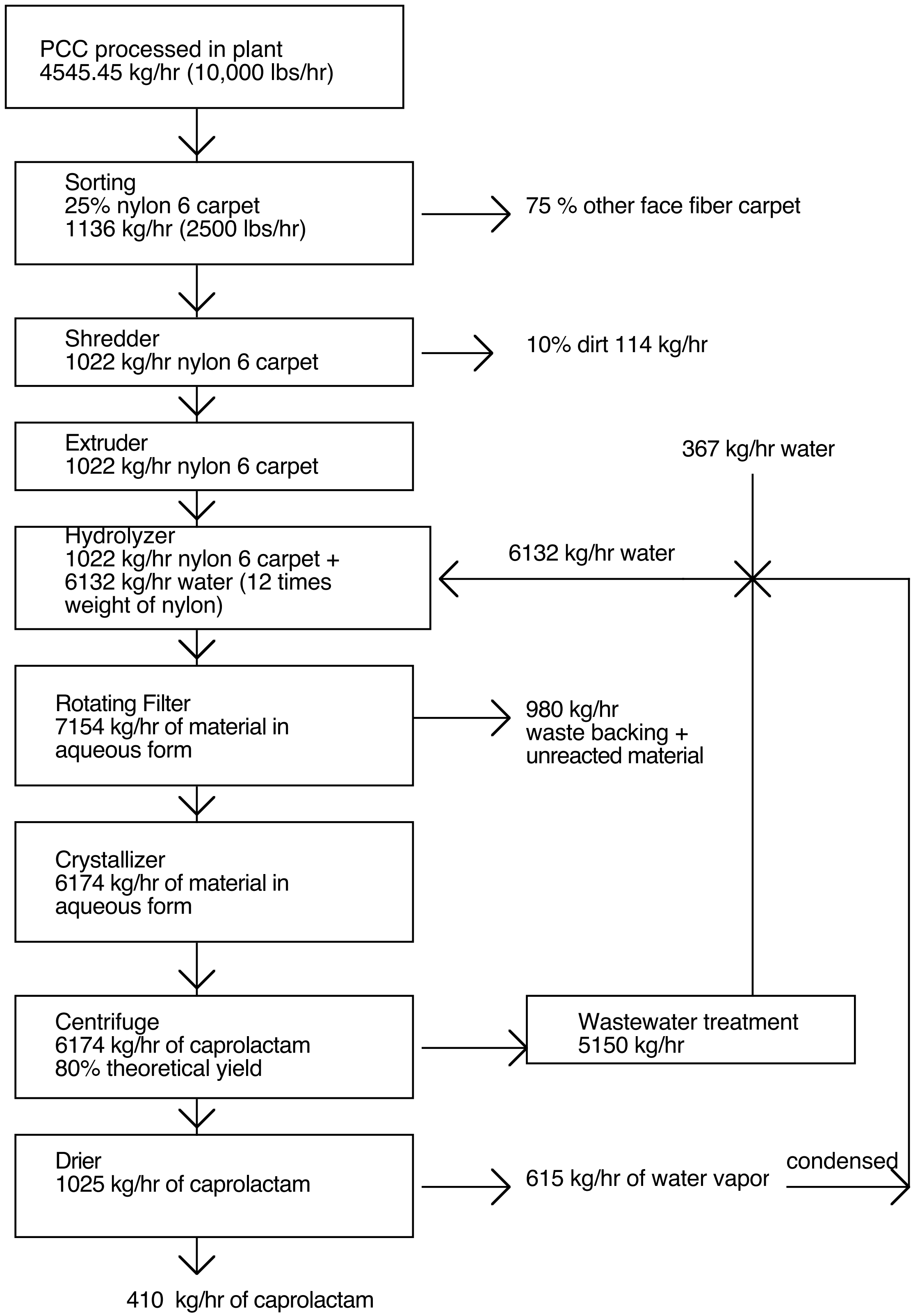

Figure 7.2 Mass balance of nylon 6 depolymerization

In the case of nylon 6,6 carpet, two products are formed, hexamethylene diamine and adipic acid, which in water solution are present primarily as the salt of hexamethylene diamine with adipic acid [21]. The U.S. patent 4,605,762, does not give any estimates on the yields of monomers recovered in the process. The thermal hydrolysis degradation of nylon 6,6 reported by Ogale using p-toluene sulfonic acid also does not provide any estimates of yields obtained. The yield should, from experience, be at least 80 %, just as in the previous case of nylon 6 depolymerization, to ensure that the process is profitable enough for a company to invest in such a plant. So assuming that the yields of hexamethylene diamine and adipic acid are both 80%, the corresponding mass balance is presented in Figure 7.4

The process diagram showing the preferred apparatus arrangement for depolymerizing nylon 6,6 is shown below in Figure 7.3.

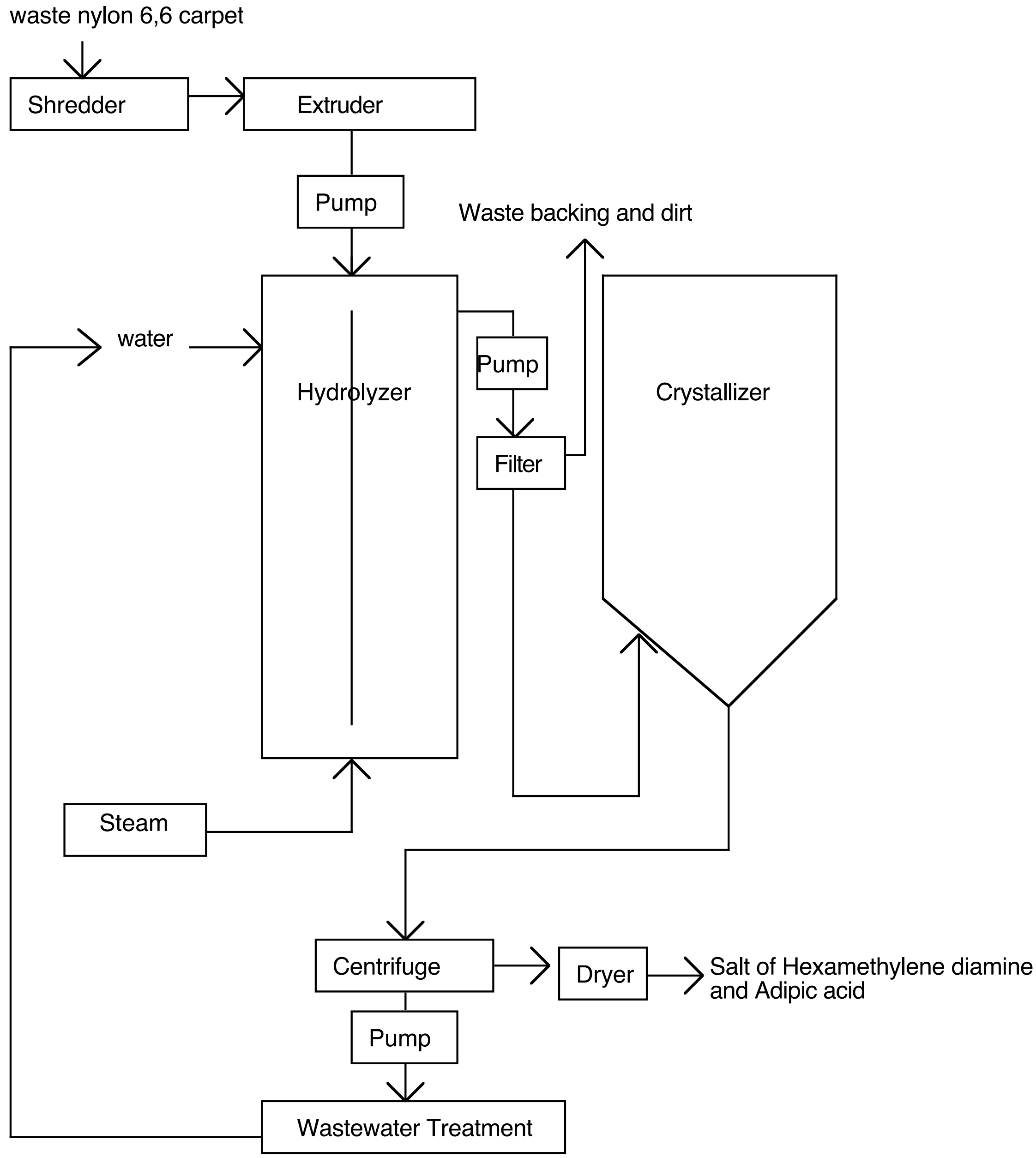

Figure 7.3 Hydrolysis reaction set up for depolymerization of nylon 6,6

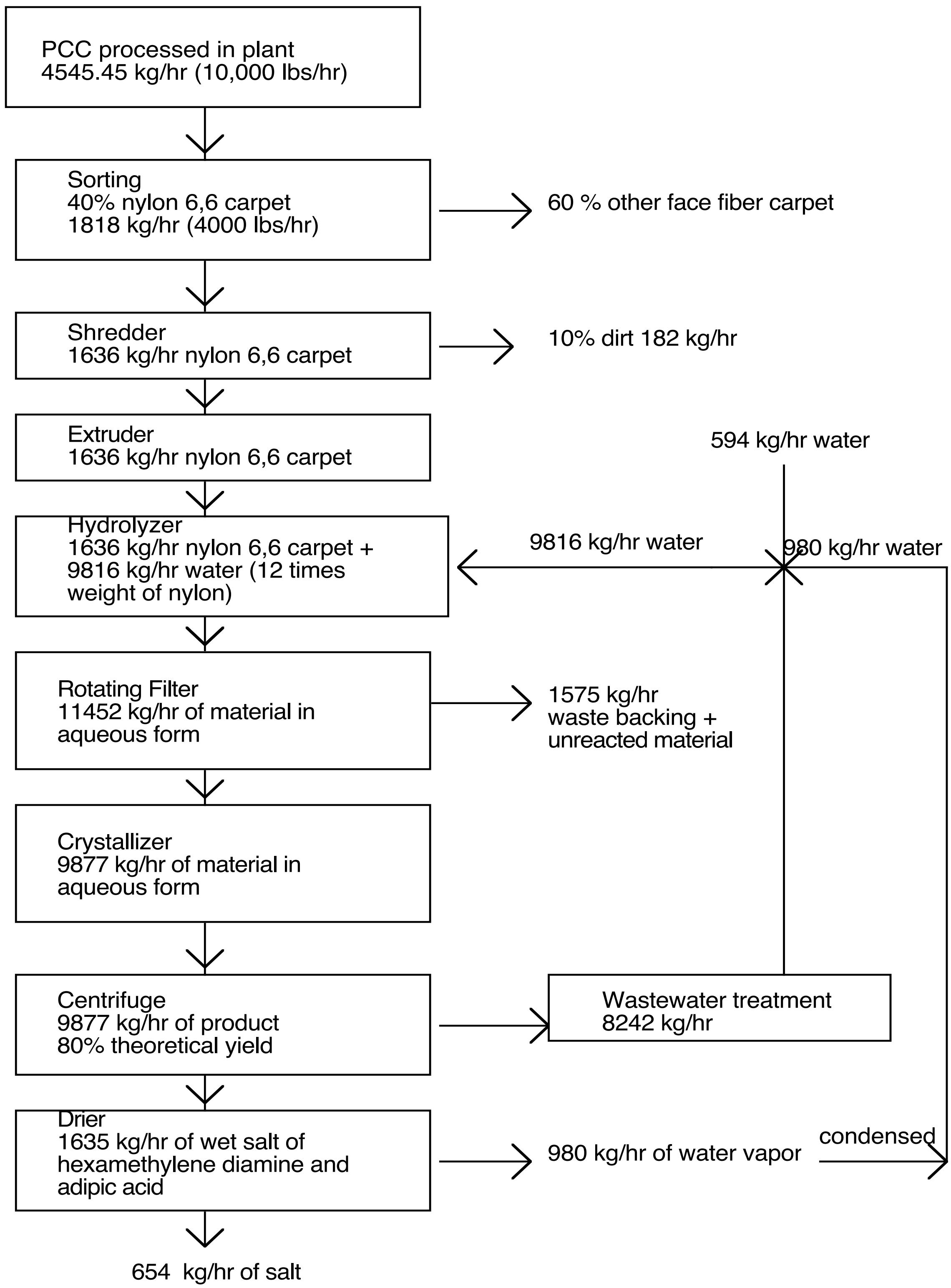

Figure 7.4 Mass balance of nylon 6,6 depolymerization

7.1.2 Equipment Description

In the above figures the following equipment were illustrated:

Extruder

An extruder is used to discharge shredded carpet pieces to the hydrolyzer directly into the upper part of the hydrolyzer.

Hydrolyzer

The shredded nylon waste carpet is fed in a continuous manner to a vertical cylindrical hydrolyzer, which has a vertical plate in its interior dividing the hydrolyzer into two semicircular sections. In a simultaneous manner, water is injected or pumped to the hydrolyzer in a suitable proportion . This proportion is about 2 to 20 times the amount of the nylon. The hydrolyzer may be equipped with a source of heating, such as a jacket with a heating fluid such as steam. High pressure steam is introduced into the lower portion of the hydrolyzer underneath the level of the waste carpet material. The steam agitates the nylon waste material to provide heat transfer and to maximize contact between the waste material and water in the hydrolyzer. The nylon will be found at the bottom of the hydrolyzer as it is denser than water. The supernatant liquid will be an aqueous solution of the products of the hydrolysis reaction. [21]

The vertical plate in the hydrolyzer does not extend along the whole length but will leave a free space both in the upper and lower parts. The entry of water is on one side of the hydrolyzer, the side corresponding to the supply of the polymer. The bottom of the hydrolyzer is equipped with two connections – one of which will be used for the introduction of steam, and the other for the drainage of the hydrolyzer. Water is introduced to the hydrolyzer in a proportion that is 2-20 times the amount of the polymer. The quantity of water should be sufficient so as to keep the products dissolved as they are formed. The hydrolysis temperature varies between 200 and 300 deg C. The greater the temperature, the greater the rate of reaction, the higher the pressure in the equipment and the higher will be the solubility of products. The pressure in the hydrolyzer is preferably between 15 and 100 atmospheres. The pressure is a function of temperature. The residence time of the material being hydrolyzed is preferably between 5 minutes and 6 hours. The residence time required depends on the temperature used [21].

Rotating filter system

Rotating filtration is based on cylindrical Couette flow with a rotating porous inner cylinder. In this operation the waste backing and dirt is separated from the reacted material. The dynamics of the flow field in the rotating filter result in particles tending to be transported away from the porous inner cylinder, thus contributing to the antiplugging character of rotating filter devices. [43]

Crystallizer

The supernatant liquid removed from the hydrolyzer is sent to a continuous crystallizer. Cooling in the crystallizer may preferably be attained by just venting the pressure. The residence time in the crystallizer is from 5 minutes to 5 hours. The residence time in the crystallizer will depend on the average size of crystals desired.

The larger the crystal size, the greater the residence time. The temperature in the crystallizer is maintained between -10 and 200 deg C [21].

A continuous crystallizer which is made up of a vertical tank and a conical bottom, and which is equipped with venting means for release of pressure is shown in the process diagram. The crystallizer is connected to the discharge tube of the filter cartridges on the hydrolyzer by means of a line and an automatic valve, which permits passage of all the liquid in addition to a small quantity of steam, which has an agitation function in the hydrolyzer.

Centrifuge

The suspension obtained from the crystallizer is separated continuously using a centrifuge. A centrifuge is a piece of equipment, generally driven by a motor, that puts an object in rotation around a fixed axis, applying a force perpendicular to the axis. The centrifuge works using the sedimentation principle, where the centripetal acceleration is used to separate substances of greater and lesser density.

A continuous centrifuge, which receives the discharge from the crystallizer and continuously discharges wet crystals towards the dryer, is shown in the process diagram [21].

Dryer

Drying is typically a batch operation. This process is fundamentally thermal and doesn't involve mechanically separating the liquid from the material, such as in filtration or centrifugation. Drying is a mass transfer process resulting in the removal of water moisture or moisture from another substance, by evaporation to end in a solid state.

In this case, air, applies the heat by convection and carries away the vapor as humidity. Heating of air reduces relative humidity of air, which is the driving force for drying. Higher temperatures also speed up diffusion of water inside the solids, so drying is faster. However, product quality considerations limit the applicable rise to air temperature. By controlling pressure and the heat introduced to the dryer the material can be dried faster than at normal atmosphere.

The dryer consists of an enclosed, thermal-jacketed vessel that serves as the drying chamber. [44]

Wastewater treatment

The wastewater from the process is treated in facility and recycled back to the hydrolyzer.

7.1.3 Basis

The nylon 6 depolymerization facility only uses 25% of the collected carpet which is nylon 6 for the depolymerization process. Similarly, the nylon 6,6 depolymerization facility uses 40% of the collected carpet which is nylon 6,6 for the depolymerization process. The rest, 35%, of the collected carpet can be diverted to make carpet underlay. The facility is a centralized one.

The amount of carpet disposed per year in the US is 2.3 billion kg. This corresponds to a disposal rate of approximately 7.6 kg/yr/person in the US. A centralized facility such as the one described above could be located in a place like Atlanta. This facility would collect waste carpet from all of Georgia, Alabama, and Tennessee (neighboring regions). This would correspond to a population of about 20 million people. They would dispose 76 million kg of carpet every year. Assume about 30% of that carpet gets collected and shipped to the processing facility. This corresponds to 46 million kg of carpet processed per year in such a facility. This facility runs 350 days a year for three shifts of 8 hours per day with 10 operators/shift: one for the shredder and extruder, two for the hydrolyzer, two for the filter and crystallizer, one for the centrifuge and dryer, two for the wastewater treatment facility, and two for the underlay facility. The operators are also in charge of general maintenance of the equipment. Hence, the amount of carpet processed here would be 5000 kg/hr if 23 million kg of carpet need to be recycled per year. The calculations for this facility have been based on a round-off number of 10,000 lb/hr or 4,545 kg/hr of carpet being processed. This processing capacity is fairly close to the amount of carpet that would be collected from these regions and hence, has been used as a reasonable basis for the calculations.

7.2 Inventory Analysis

7.2.1 Mechanical Separation

Shredding: The shredder reduces unbaled carpet to fibers preferably between 4-10 cm using screens of about 5 cm. This involves little removal of face fiber from backing. The basis on which the estimate has been listed below for power usage depends on the material being processed. Detailed information is given in Appendix, A. To process 4545 kg/hr, three shredders which process 1364 kg/hr each are used simultaneously in the facility.

Equipment	**Power Used (HP)**	**Material Capacity (kg/hr)**	**Cost (USD)**
Shredder	300	1364	150,000

7.2.2 Extruder

Extrusion: The extruder is used effectively as a pressurized transport device for the shredded carpet into the hydrolyzer. The power usage and the cost of the equipment have been obtained from J.Muzzy [37].

Material processed (lb/hr) = 0.01 x (screw diameter in mm) $^{2.7}$ x (screw speed in RPM/500), where 500 is the max RPM

Power consumption (HP) = 0.15 x Material processed (lb/hr)

0.15 is an empirical factor that depends on material being processed.

Extruder cost ($) =1900 x (screw diameter in mm) $^{1.25}$

The power required and cost of equipment for processing nylon 6 has been shown below.

Equipment	Power Used (HP)	Material Capacity (kg/hr)	Cost (USD)
Extruder	336	1022	623,500

Hydrolyzer

Hydrolyzer: A vertical cylindrical hydrolyzer is used to depolymerize the nylon waste in the absense of any reactants other than water. The temperature is between 200 and 300 deg C. The pressure is between 15 and 100 atm. The water to polymer ratio is between 2 and 20. The residence time for the reaction is between 5 minutes to 6 hours. A vertical pressure vessel containing little or no internals has been used. This vessel is cylindrical in shape, with an inside diameter, D_i, and consists of a cylindrical shell of length, L. The costing method used is based on D_i and L, with a correction for design pressure. [31a]

$C_p = F_M C_V + C_{PL}$, where C_V is the cost of the empty vessel, including nozzles, manholes, and supports, and C_{PL} is the cost of platforms and ladders [31a]

$C_V = \exp\{6.755 + 0.18255[\ln(W)] + 0.02297[\ln(W)]^2\}$, where W is the weight in pounds of the shell [31a]

$C_{PL} = 285.1(D_i)^{0.7360}(L)^{0.70684}$ [31a]

For a vessel with dimensions, $D_i = 6$ ft, $L = 30$ ft, operating pressure $P_o = 80$ atm, the design pressure is

$P_d = \exp\{0.60608 + 0.91615[\ln(P_o)] + 0.0015655[\ln(P_o)]^2\} = 88$ atm. [31a] This higher pressure takes safety into consideration in the design of the reactor. If the reactor is made of stainless steel, a commonly used material in non-corrosive environments, for a design temperature between 392 deg F and 572 deg F, the maximum allowable stress, S, is 15,000 psi.

The wall thickness of the vessel is

$t_p = P_dD_i/(2SE-1.2P_d)$, where E is fractional weld efficiency. E accounts for the integrity of the weld for the longitudinal seam. [31a] For a vessel up to 1.25 in. in thickness, only a 10% spot X-ray check of the weld is necessary and hence, a value of 0.85 has been used.

$t_p = 0.02$ ft

The weight of the shell is given by

$W = \Pi(D_i + t_s) (L + 0.8D_i)t_s\rho$, where $\rho = 500$ lb/ft^3 for stainless steel and $t_s = t_p + 2(1/8^{th}$ of an inch) = 0.04 ft [31a]. The extra thickness is an allowance for corrosion and wind load considerations.

W = 13,200 lb

C_v = \$ 38,530

C_{PL} = \$ 11,800

Using a material factor of 1.2 for stainless steel, C_P = \$ 50,330

Heat duty for the process of nylon 6 depolymerization would be calculated in two parts:

Heat duty for heating water = $m_{water}(Cp\Delta T)$ = 4820 kW, where ΔT = 300 deg C – 25 deg C = 275 deg C, Cp = 4.187 kJ/kg.K, and m_{water} = 9,816 kg/hr

Heat duty for nylon depolymerization = $m_{nylon}(\Delta H_{rxn})$ = 66 kW, where ΔH_{rxn} = 146 kJ/kg [46], and m = 1636 kg/h .

ΔH_{rxn} is obtained by multiplying the exothermic heat of polymerization for nylon 6 (-16.5 kJ/mol) by the molecular weight of caprolactam (113 g/mol).

Total heat duty = 4890 kW = 6550 HP.

Equipment	Power Used (HP)	Material Capacity (kg/hr)	Cost (USD)
Reactor	6550	11,450	50,330

7.2.4 Filter System

Filter: A rotary filter is used to separate the slurry of material exiting the hydrolyzer. This filter separates the backing, dirt and unreacted material from the caprolactam that is dissolved in the water. The price of a continuous filter has been obtained from Figure 15.39 in [32c]. The filter separates ~ 980 kg of solid material from 10,470 kg of aqueous material every hour. The viscosity of the liquid which is mostly water is about 1 cP. The equation used to calculate the filtering area is calculated from

$$\frac{\theta \Delta p}{\nu / A} = 0.5 \alpha \omega \left(\frac{\nu}{A} \right) + \alpha \omega \mu \nu_F$$, where

Δp is the pressure drop across the filter

A is the area of the filtering surface

ω is the mass of dry cake solids per unit volume of filtrate = 980 kg/10470 m^3

μ is the viscosity of the filtrate = 1 cP

ν is the volume of filtrate delivered in time θ = 10470 m^3/hr

α is the specific cake resistance. This value is experimentally calculated. Using a value used in example 15.10 of [32c]: estimating the filtering area required to remove solid material from a slurry, assume α = 870

ν_F is the fictitious volume of filtrate necessary to lay down a cake of thickness t_F, using the same example 15.10 in [32c], assume $\nu_F = 4.51 \times 10^{-3}$ m^3/m^2

$\Delta p = (10470 \text{ kg} - 980 \text{ kg}) \times 9.8 \text{ m/s}^2 / A$

By iterating values of A, $A \sim 600 \text{ m}^2$

Equipment	**Power Used (HP)**	**Material Capacity (kg/hr)**	**Cost (USD)**
Filter	Neg.	11,450	100,000

7.2.5 Crystallizer

Crystallizer: A continuous crystallizer, equipped with vents, is used to release pressure for cooling. The temperature is maintained from -10 to 200 deg C. The residence time is 5 minutes to 5 hours. The estimates for material capacity and cost have been obtained from Table 16.32 of [31a]. The equation for the purchase cost of the equipment is $27{,}500W^{0.56}$, where W is the tons of material processed per day. The allowed range of W is 10 – 1,000 ton/day. Assume the material enters the crystallizer at 200 deg C and is cooled to 20 deg C, corresponding cooling duty would be calculated in two parts:

Cooling duty for forming crystals of monomer = $m_{product}(Cp\Delta T + \Delta H_{fusion})$ = 82 kW , where Cp = 1.47 kJ/(kg deg C), ΔT = 180 deg C, ΔH_{fusion} = 188 kJ/kg, and $m_{product}$ = 654 kg/h [45]

Cooling duty for cooling water = $m_{water}(Cp\Delta T)$ = 1,930 kW, where Cp = 4.187 kJ/(kg deg C), ΔT = 180 deg C, and m = 9,223 kg/h.

Total cooling duty = 2,100 kW

.

Equipment	**Power Used (HP)**	**Material Capacity (kg/hr)**	**Cost (USD)**
Crystallizer	2700	9,877 kg/hr	99,150

7.2.6 Centrifuge

Centrifuge: A continuous centrifuge with a washing device receives material from the crystallizer and discharges it towards the drier. The power used has been obtained from [40]. For a flow rate of 80 – 200 GPM, the machine used 50 HP. The density of polycaprolactam is 1.12 g/c.c [39] and the density of water is 1 g/c.c. Based on these two numbers, material throughput in the centrifuge corresponds to about 104 GPM. The cost of the centrifuge is obtained from Table 16.32 of [31a]. The equation for the purchase cost of the equipment is $120{,}000S^{0.30}$, where S is the tons of material processed per hr. The allowed range of S is 1-120 ton/hr.

Equipment	**Power Used (HP)**	**Material Capacity (kg/hr)**	**Cost (USD)**
Centrifuge	50	9,877	240,000

7.2.7 Dryer

Dryer: A granular product, caprolactam, or salt of hexamethylene diamine and adipic acid, containing 2.5 kg of water per kg of dry solid enters the tumble dryer at 20 °C and leaves at 30 °C. A final moisture content of 0.02 kg of water per kg of dry solids is to be achieved in this drying process. Air is available at 60% relative humidity. This air is preheated to 100 °C before it enters the dryer. The solids enter the dryer at 0.22 kg/s with a density, ρ_s, of 1.01 g/cc. The heat capacity of air is 1 kJ/kg °C while that of the product is 1.47 kJ/kg °K.

Assume a solid velocity, v_s, of 0.01 m/s and solid occupancy of 12.5% in the dryer

Area = pi x D x D/4 = $m_s/\rho_s v_s/0.125 = A_s/0.125 = 0.175\ m^2$

The price of a tumble dryer has been taken from Figure 15.33 of [32c], \$10,000

The energy, Q, used to heat the product is from 20 °C to 70 °C is given by $m(Cp\Delta T) = 33.4$ kW, where Cp = 1.47 kJ/kg °C [32c] and m = 1635 kg/hr. The amount of air required to achieve this drying action is given by $m = Q/(Cp\Delta T) = 1603$ kg/hr, where Cp = 1 kJ/kg °C and ΔT = 100 °C - 25 °C = 75 °C. To calculate the power used in the air dryer, an efficiency of 30% has been assumed.

Equipment	Power Used (HP)	Material Capacity (kg/hr)	Cost (USD)
Dryer	150	1635	10,000

7.2.8 Storage Tank

Storage tank: The hexamethylene diamine, adipic acid and caprolactam produced are stored in storage tanks located in the plant before being shipped off to the next destination for further purification. For purpose of calculations it has been assumed that the tanks should be large enough to accommodate storage of about a week's worth of material produced. The cost of the storage tank is obtained from Table 7-15 [44]. A 61 gallon fiber drum with a 400 lb load limit for dry products has been selected for storage of the products, caprolactam, and the salt of hexamethylene diamine and adipic acid. The unit cost of the drum is \$7.85. The usable volume of the drum is 0.23 m^3 [10]. Using a density of 1.01 g/cc for caprolactam, ~ 470 drums are needed for storing a week's yield of product from the facility.

Equipment	Power Used (HP)	Material Capacity (kg/hr)	Cost (USD)
Storage tank	Neg.	654	3,700

7.2.9 Wastewater Treatment

Wastewaster treatment facility: The water used in the hydrolysis is treated and recycled back to the hydrolysis zone. The cost of the treatment equipment is obtained from Table 16.32 in [31a]. The equation for the purchase cost of the equipment is $11{,}700Q^{0.64}$, where Q is the gallons of wastewater treated per minute. This equipment is used to treat 8,250 kg/hr of wastewater. Power requirements have been based on [42]. The facility has a sedimentation stage where the waste is allowed to pass slowly through large primary sedimentation tanks. The tanks are large enough that sludge can settle and floating material such as grease and oils can rise to the surface and be skimmed off. Anaerobic digestion, a bacterial process, is then carried out in the absence of oxygen. The process is mesophilic digestion, in which sludge is fermented in tanks.

Equipment	**Power Used (HP)**	**Material Capacity (kg/hr)**	**Cost (USD)**
Wastewater treatment	~1	8,250	117,000

7.3 Labor Requirement

The guidelines for estimating labor-related operations have been summarized in Seader, Seider and Lewin [31b]. Direct wages and benefits (DW&B) and other wages propotional to it are an important fraction of the cost of manufacture. Table 17.1 in [31b] lists labor related charges associated with operations.

Using a value of $30/operator-hr, the direct wages and benefits (DW&B) annually are calculated to be $30/operator-hr x 10 operators/shift x 3 shifts x 8 hrs/day x 350 days/year, which is $ 2,520,000.

Operations related costs are as follows: direct salaries and benefits for supervisory and engineering personnel are 15% of DW&B and operating supplies and services are 6% of DW&B. In addition, $52,000/(operator/shift)-yr for technical assistance to manufacturing and $57,000/(operator/shift)-yr for control laboratory are added [31b].

Annual DW&B = $ 2,520,000

Using Table 17.1 in [31b], the other annual labor-related operations costs are

Direct Salaries and benefits for supervision = 0.15($2,520,000) = $ 378,000

Operating supplies and services = 0.06($2,520,000) = $ 151,200

Technical assistance to manufacturing = $52,000(4) = $208,000

Control laboratory = $57,000(4) = $228,000

A second category of labor costs is associated with maintenance of the processing plant. The equipment must be kept in working order, with repairs and replacement of parts made as needed. Maintenance wages and benefits are a fraction of the total depreciable capital. In the case of solids-fluids processing, according to [31b], it is 4.5% of C_{TDC} (Total depreciable capital). Salaries and benefits for engineers and supervisory personnel are 25% of MW&B (Maintenance wages and benefits), while maintenance overhead is 5% of MW&B. The total annual cost of maintenance runs at 8-11.5% of C_{TDC}.

C_{TDC} has been calculated using pieces of information from Table 16.9 in Seader, Seider and Lewin [31b]. These items are the cost of site preparation and service facilities, allocated costs for utility plants and related facilities, and cost for contingencies and contractor's fees.

Total cost of purchased equipment = $ 4,700,000

Equipment includes shredder, extruder, hydrolyzer, crystallizer, centrifuge, filter, dryer, storage vessel and water treatment tank.

Total bare-module cost for on-site equipment = $ 8,900,000, which is the sum of the bare-module costs of the process equipment.

The bare module cost is the product of the purchase cost of an equipment and its bare module factor, F_{BM}. A detailed list of all the F_{BM} values used for the above listed equipment is shown in Appendix C. The bare module factors, F_{BM} have been obtained from Guthrie [34] for various types of equipment. This factor takes into account the field materials for installation of the equipment, direct field labor charges, freight charges, contractor engineering expenses, and construction overhead.

Cost of site preparation and service facilities = cost of purchased equipment x 0.8 = \$ 3,800,000.

Site preparation involves making land surveys, dewatering and drainage, surface clearing, addition of fencing, clearing of roads, sidewalks, and landscaping. Service facilities include maintenance shops; and laboratories for feed and product testing.

This value of 0.8 is a ratio factor used for estimating capital investment items based on delivered equipment cost. [32a]. The factors vary depending on the type of process plant being considered.

Cost of contingencies and contractor's fee = cost of purchased equipment x 0.52 = \$ 2,500,000. This value of 0.52 is also a ratio factor based on delivered equipment cost [32a]. Contingencies are unanticipated costs incurred during the construction of a plant.

Using Table 17.1 in [31b], the other maintenance labor-related operations costs are

Total depreciable costs, C_{TDC} = $ 15,000,000

Maintenance wages and benefits (MW&B) at 5% of C_{TDC} = $ 756,000

Salaries and benefits at 25% of MW&B = $ 190,000

Materials and services at 100% of MW&B = $ 756,000

Maintenance overhead at 5% of MW&B = $ 38,000

7.4 Summary

The power required, the material processed and the labor utilized in the nylon depolymerization in the centralized facility have been calculated in this chapter. The total power required to run the equipment is ~ 5420 HP. The amount of material processed by the depolymerization facility is 1136 kg/hr of nylon 6 carpet and 1818 kg/hr of nylon 6,6 carpet. This produces a yield of 410 kg/hr of caprolactam and 654 kg/hr of the salt of hexamethylene diamine and adipic acid. The amount of material processed by the underlay manufacturing facility is 1590 kg/hr of non nylon waste carpet. This produces a yield of 715 kg/hr of carpet underlay. This facility runs 350 days a year for three shifts of 8 hours per day with 10 operators/shift: one for the shredder and extruder, two for the hydrolyzer, two for the filter and crystallizer, one for the centrifuge and dryer, two for the wastewater treatment facility, and two for the underlay facility. The facility that has concurrent procedures of nylon 6 and nylon 6,6 depolymerization and underlay manufacturing will be compared with the other processes presented. An economic viability study of all the recycling procedures will be presented in a later chapter.

CHAPTER 8
SHIPPING PALLET PRODUCTION PROCESS

8.1 Goal and Scope Revisited

The economic viability of the shipping pallet production process will be studied by taking inventory of all the energy required, the material processed and the labor utilized.

8.1.1 Overview

The process diagram showing the preferred apparatus arrangement for manufacturing shipping pallets is shown in Figure 8.1.

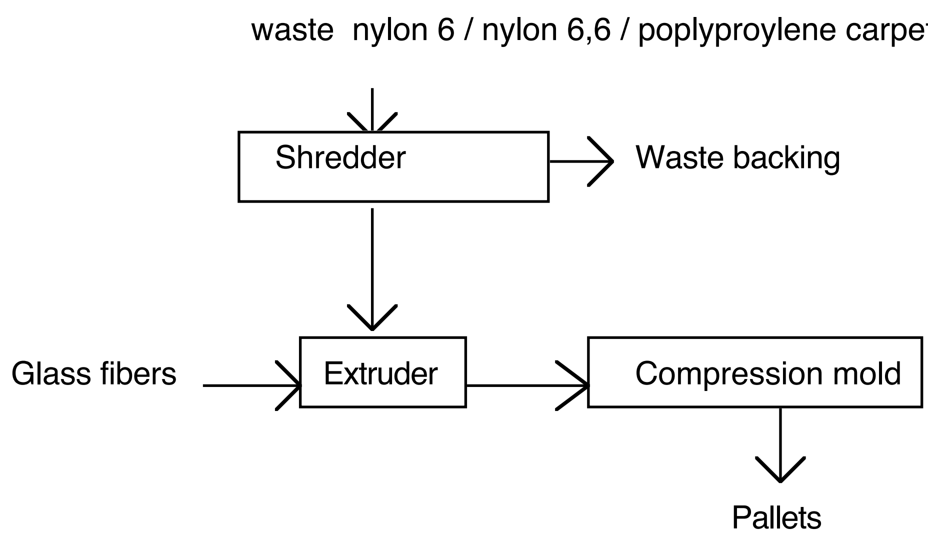

Figure 8.1 Pallet production process

This process can be used in conjunction with the nylon 6 depolymerization process using an extruder. It can also be used as a stand-alone carpet recycling option (the case presented in this chapter).

The waste carpet first gets sorted into nylon 6, nylon 6,6, and polypropylene carpet. The waste carpet carries 10% of its weight as dirt. This dirt and some of the backing falls off after the shredding process. As a general rule, 50% of carpet's weight accounts for the face fiber and the rest of it accounts for the backing. The carpet is shredded down to smaller pieces, which separates some of the face fiber from the backing. These pieces are then compounded with 25% by weight glass fibers in an extruder. The extrudate is then sent to a compression molding press that forms the shipping pallets. This process is depicted in Figure 8.2.

This process usually has a 90% yield of the collected carpet. The 10% loss arises from the shredding operation where 10% of the carpet gets discarded.

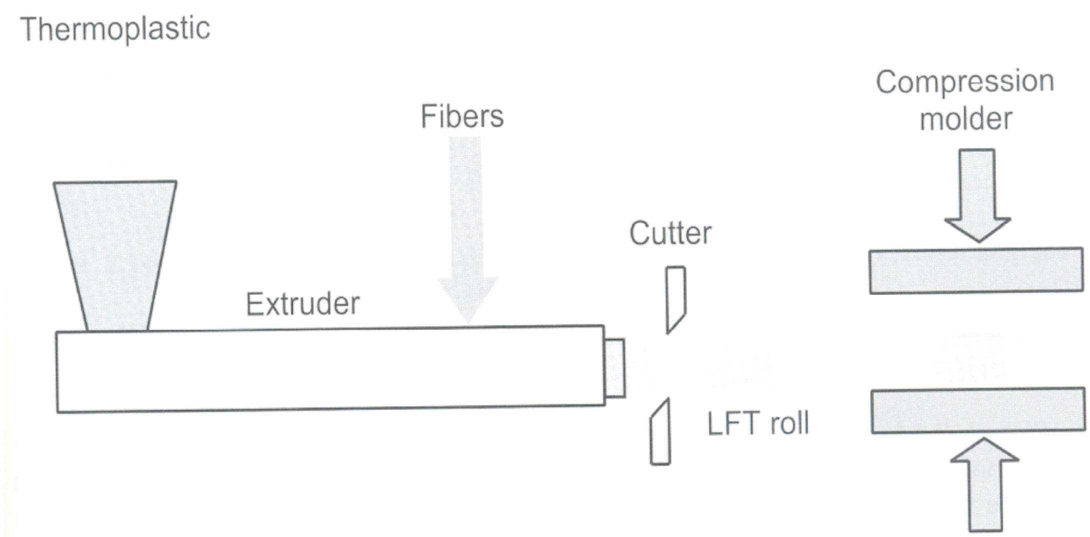

Figure 8.2 Schematic of pallet production process [47]

8.1.2 Basis

The pallet production facility uses all of the collected carpet in the manufacturing process. The facility is also decentralized one.

The amount of carpet disposed per year in the US is 2.3 billion kg. This corresponds to a disposal rate of approximately 7.6 kg/yr/person in the US. A city such as Atlanta has a population of about 5 million people and hence disposes 38 million kg of carpet every year. Assume about 30% of that carpet gets collected and shipped to the processing facility in that city. This corresponds to 11 million kg of carpet processed per year in such a facility. This facility runs 330 days a year for one shift of 8 hours per day with 3 operators/shift: one operator to run the shredder, one to run the extruder, and one more for the compression molding press. The three operators are also responsible for maintenance of the equipment and quality control of the shipping pallet. Hence, the amount of carpet processed here would be 4300 kg/hr if 11 million kg of carpet need to be recycled per year. The calculations for this facility have been based on a round of number of 10,000 lb/hr or 4545 kg/hr of carpet being processed. This base amount is fairly close to the 4300 kg/hr calculated earlier, and hence is a reasonable estimate for the amount of carpet being collected and processed by such a decentralized facility.

The mass flow of the above process is shown in Figure 8.3

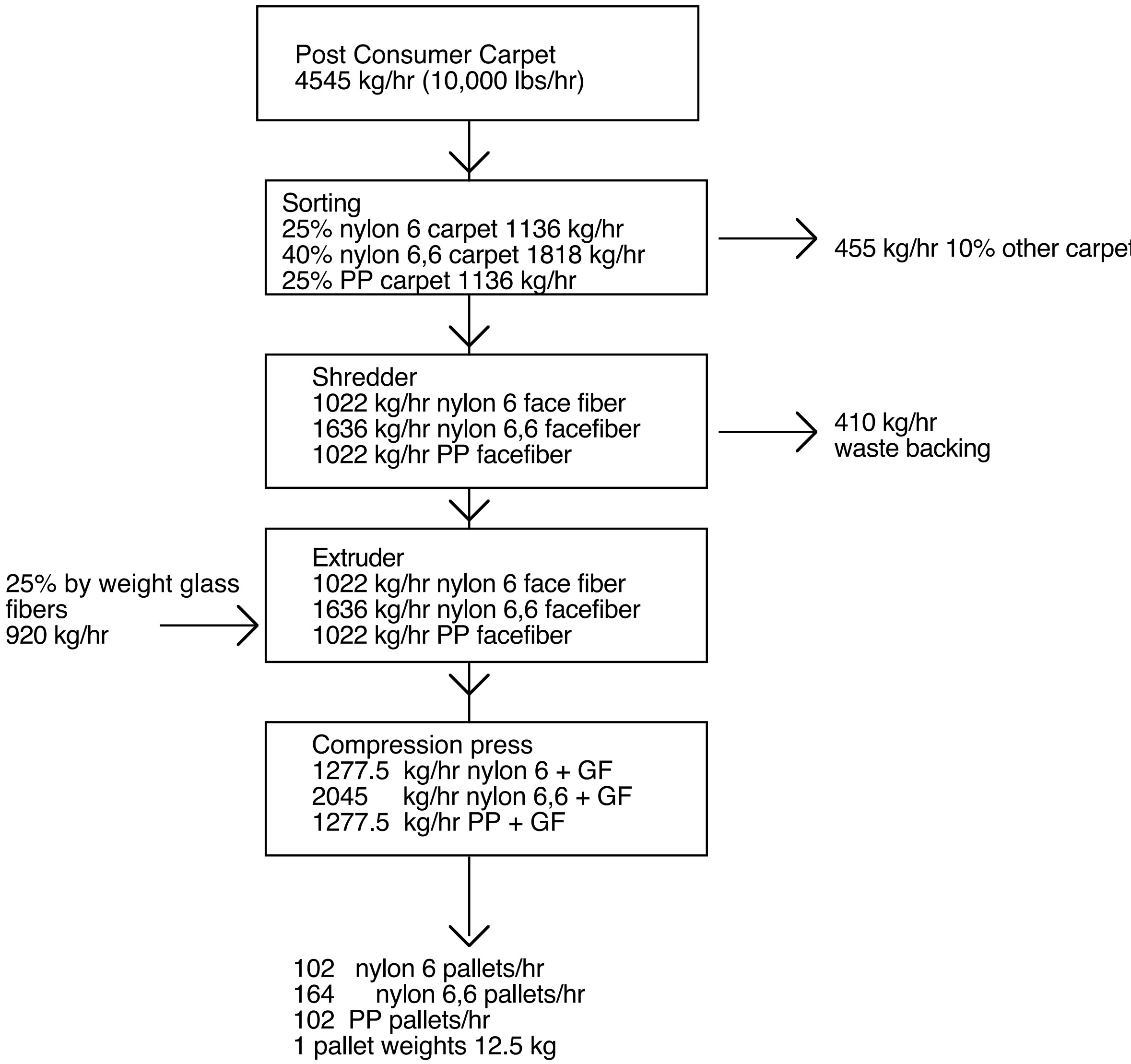

Figure 8.3 Mass flow diagram for the pallet manufacturing process

8.1.3 Equipment Description

Compression molding press

The main component of compression molding press is mold filling. Today, most compression molds are positive compression molds like the one shown in Figure 8.4. With this type of mold the charge weight is measured exactly before it is placed inside the cavity. Since there is variation in the weight of the molding compound, it is often necessary to place the compound on the center of the charge to complete the full weight of the part. The mold is closed rapidly until both mold halves touch the charge, and then slows down, causing the material to flow and fill the mold cavity. Flow and deformation forces air voids out of the material, eliminating some porosity in the final compound. During flow, the orientation of the fibers is changed, which has a profound impact on the properties of the finished part. It is generally desirable to have a random orientation in a final part. Due to the random loading the part may experience, it is necessary for it to be equally strong in all directions. [47]

Once the mold is full, a constant force is maintained on the material, as the cooling of the resin progresses. Once the part has solidified, the part is removed and allowed to cool down. The compression molding process takes a short amount of time (seconds/minutes) to accomplish. [47]

Each pallet weights about 12.5 kg. This allows for the production of ~100 nylon 6, ~ 100 polyproylene pallets per hour and ~160 nylon 6,6 pallets per hour.

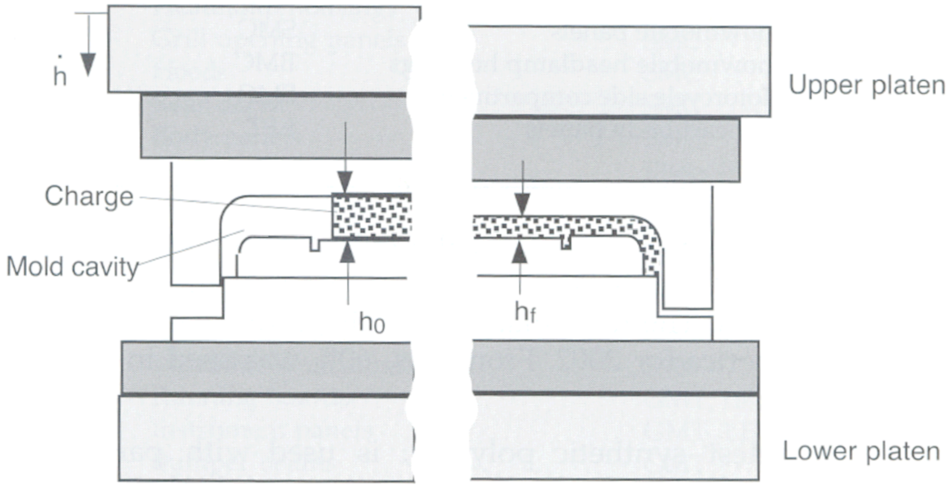

Figure 8.4 Compression mold [47]

8.2 Inventory Analysis

8.2.1 Mechanical Separation

Shredding: The shredder reduces unbaled carpet to fibers preferably between 4-10 cm using screens of about 5 cm. This involves little removal of face fiber from backing. The basis on which the estimate has been listed below for power usage depends on the material being processed. Detailed information is given in Appendix, A. To process 4545 kg/hr of collected waste carpet, three shredders which process 1364 kg/hr each are used simultaneously in the facility.

Equipment	**Power Used (HP)**	**Material Capacity (kg/hr)**	**Cost (USD)**
Shredder	300	1364	150,000

8.2.2 Extruder

Extrusion: Each type of carpet, nylon 6, nylon 6,6, and polypropylene is heated to a molten state by a combination of heating elements and shear forces from the extrusion screws. The extruder is used effectively as a as a mixing device where the face fiber is mixed with glass fibers in the amount of 25% by weight of the face fibers. The power usage and the cost of the equipment have been obtained from J.Muzzy [37].

Material processed (lb/hr) = 0.01 x (screw diameter in mm) $^{2.7}$ x (screw speed in RPM/500), where 500 is the max RPM

Power consumption (HP) = 0.15 x Material processed (lb/hr)

0.15 is an empirical factor that depends on material being processed.

Extruder cost (\$) =1900 x (screw diameter in mm) $^{1.25}$

The extruder has been sized to handle the different amounts of the different types of face fiber that get processed.

Equipment	Power Used (HP)	Material Capacity (kg/hr)	Cost (USD)
Extruder	1200	3600	1,124,000

8.2.3 Compression molding press

Compression molding press: The material from the extruder is molded into a pallet in a short time (seconds/minutes) using a compression molding press.

For a compression press using a certain ton force, the correlation given by J. Busch is

Cost of compression press = 9000 x (clamping force in tons) $^{0.57}$, [48]

where clamping force = (pressure x area) / 2000 [49]

For a pressure of 200 psi (high pressure) and area of 40 inch by 48 inches, the clamping force is 192 tons.

For a compression mold using a certain part weight, the correlation given by J. Throne is

Cost of compression mold = 19000 X (part weight) $^{0.76}$ for high pressure [50]

Cost of compression mold = 10000 X (part weight) $^{0.27}$ for low pressure [50]

The estimates below were calculated using a clamping force of 192 tons force and part weight of 12.5 kg/pallet. As a rule, 2.5 tons of clamping force is required for every square inch of projected area of the molded item. The projected area is the maximum area parallel to the clamping force, i.e., the platens. The cycle time to form one pallet is 2 minutes. Hence to process ~ 160 pallets/hr, about 5 compression presses should operate in parallel.

A 200 ton compression molding press uses a 13 HP motor. [55]

Equipment	**Power Used (HP)**	**Material Capacity (kg/hr)**	**Cost (USD)**
Compression press + mold	13	2000	415,400

The yield of this process is about 90% of the collected carpet.

8.3 Labor Requirement

The guidelines for estimating labor-related operations have been summarized in Seader, Seider and Lewin [32b]. Direct wages and benefits (DW&B) and other wages propotional to it are an important fraction of the cost of manufacture. Table 17.1 in [32b] lists labor related charges associated with operations.

Using a value of $30/operator-hr, the direct wages and benefits (DW&B) annually are calculated to be $30/operator-hr x 3 operators/shift x 1 shift x 8 hrs/day x 330 days/year, which is $ 237,600.

Operations related costs are as follows: direct salaries and benefits for supervisory and engineering personnel are 15% of DW&B and operating supplies and services are 6% of DW&B. In addition, $52,000/(operator/shift)-yr for technical assistance to manufacturing and $57,000/(operator/shift)-yr for control laboratory are added [32b].

Annual DW&B = $ 237,600

Using Table 17.1 in [32b], the other annual labor-related operations costs are

Direct Salaries and benefits for supervision = 0.15($ 237,600) = $ 35,640

Operating supplies and services = 0.06($ 237,600) = $ 14,260

Technical assistance to manufacturing = $52,000(2) = $ 104,000

Control laboratory = $57,000(1) = $ 57,000

A second category of labor costs is associated with maintenance of the processing plant. The equipment must be kept in working order, with repairs and replacement of parts made as needed. Maintenance wages and benefits are a fraction of the total depreciable capital. In the case of solids-fluids processing, according to [32b], it is 4.5% of C_{TDC} (Total depreciable capital). Salaries and benefits for engineers and supervisory personnel are 25% of MW&B (Maintenance wages and benefits), while maintenance overhead is 5% of MW&B. The total annual cost of maintenance runs at 8-11.5% of C_{TDC}.

C_{TDC} has been calculated using pieces of information from Table 16.9 in Seader, Seider and Lewin [32b]. These items are the cost of site preparation and service facilities, allocated costs for utility plants and related facilities, and cost for contingencies and contractor's fees.

Total cost of purchased equipment = $ 3,650,000

Equipment includes shredder, extruder, compression press and mold.

Total bare-module cost for on-site equipment = $ 7,027,500, which is the sum of the bare-module costs of the process equipment.

The bare module cost is the product of the purchase cost of an equipment and its bare module factor, F_{BM}. A detailed list of all the F_{BM} values used for the above listed equipment is shown in Appendix C. The bare module factors, F_{BM} have been obtained from Guthrie [34] for various types of equipment. This factor takes into account the field materials for installation of the equipment, direct field labor charges, freight charges, contractor engineering expenses, and construction overhead.

Cost of site preparation and service facilities = cost of purchased equipment x 0.8 = $ 1,600,000.

Site preparation involves making land surveys, dewatering and drainage, surface clearing, addition of fencing, clearing of roads, sidewalks, and landscaping. Service facilities include maintenance shops; and laboratories for feed and product testing.

This value of 0.8 is a ratio factor used for estimating capital investment items based on delivered equipment cost [32a]. The factors vary depending on the type of process plant being considered.

Cost of contingencies and contractor's fee = cost of purchased equipment x 0.52 = $ 1,035,000. This value of 0.52 is also a ratio factor based on delivered equipment cost [32a]. Contingencies are unanticipated costs incurred during the construction of a plant.

Using Table 17.1 in [31b], the other maintenance labor-related operations costs are

Total depreciable costs, C_{TDC} = $ 9,653,500

Maintenance wages and benefits (MW&B) at 5% of C_{TDC} = $ 483,000

Salaries and benefits at 25% of MW&B = $ 120,670

Materials and services at 100% of MW&B = $ 483,000

Maintenance overhead at 5% of MW&B = $ 24,000

8.4 Summary

The power required, the material processed and the labor utilized in the pallet production process have been calculated in this chapter. The total power required to run the equipment is ~ 1440 HP. The amount of material processed by the facility is 4545 kg/hr of carpet. This produces a yield of 3680 kg/hr of pallets. This facility runs 330 days a year for one shift of 8 hours per day with 3 operators/shift: one operator to run the shredder, one to run the extruder, and the third for the compression molding press. This facility will be compared with the other process that will be covered in later chapters. An economic viability study of all the recycling procedures will be presented in a later chapter.

CHAPTER 9

COMPREHENSIVE FINDINGS

9.1 Comparative Analysis

The costs associated with the operation of a carpet processing plant using the four recycling scenarios, (1) carpet underlay manufacture, (2) nylon 6 depolymerization using an extruder plus carpet underlay manufacture, (3) pallet production process, and (4) centralized depolymerization of nylon 6 and nylon 6,6 plus carpet underlay manufacture, have been calculated using a cost sheet outline provided in Table 17.1 of [31b]. This cost sheet has representative unit costs that can be used as early estimates when more exact costs are not available.

To compare alternative ventures that vie for capital investment, the pay back period, PBP, of the venture has been chosen as the profitability measure. The pay back period is the time required for the annual earnings to equal the original investment. This calculation is based on capital investment and annualized costs as outlined in Table 17.1 of [31b]. This approximate measure ignores the effect of inflation or time-value of money and uses a simple straight-line depreciation. This is only useful in the early stages of project evaluation. To calculate this value only the depreciable capital is used and the annual depreciation is added back to the net earnings because depreciation is retained by the company [31b].

PBP = Total depreciable costs / (Net earnings + Annual Depreciation)

= Total depreciable costs / Cash flow

9.1.1 Payback Period calculation

For this comparison between the alternative ventures, the amount of carpet processed per hour in all four cases has been kept constant, i.e. 10,000 lb/hr or 4545 kg/hr.

For every 4545.45 kg/hr of carpet processed (10,000 lbs/hr),

10% is dirt,

45% is face fiber, and

45% is backing.

Further 25% of all carpet collected has nylon 6 face fiber, 40% has nylon 6,6 face fiber, 25% has polypropylene face fiber and the rest is comprised of wool and other fibers.

The first three cases i.e. carpet underlay manufacture, nylon 6 depolymerization using an extruder plus carpet underlay manufacture, and pallet production process are decentralized processes. The fourth case, chemical depolymerization of nylon 6 and nylon 6,6 plus carpet underlay manufacture, is a centralized facility. This means the only significant traveling distance for the carpets in the first three cases would be from the consumers to the collection/sorting centers. The small scale processing centers could be set up at or very near the collection/sorting centers. Taking the transportation cost into account would bias the decentralized processes favorably.

However, in the third case, a centralized process, the carpet travels from the consumers to the collection/sorting centers and then to the processing facility. This large scale centralized facility could be as much as 500 miles or more away in distance from the collection centers.

Case Studies

Case 1 – Carpet underlay manufacturing process

All the carpet collected goes into decentralized underlay manufacturing facilities. These facilities run 330 days a year for one shift of 8 hours per day.

Case 2 – Nylon 6 depolymerization using an extruder plus carpet underlay manufacture

All the carpet collected goes into decentralized facilities where 25% of the collected carpet is sent to the depolymerization process and the rest is recycled to make underlay. These facilities run 330 days a year for one shift of 8 hours per day.

Case 3 – Shipping pallet production facility

All the carpet collected goes into decentralized facilities where its gets sorted into nylon 6, nylon 6,6, and polypropylene carpet. Then the sorted carpet is mixed with glass fibers to make shipping pallets. These facilities run 330 days a year for one shift of 8 hours per day.

Case 4 – Chemical Facility + Underlay Process

The centralized chemical plant sends the nylon 6 and nylon 6,6 carpet to the hydrolysis process and sends the rest of the carpet (35%) to the underlay manufacturing system. These facilities run 350 days a year for three shifts of 8 hours per day.

Cash flow for each of the three cases listed above has been calculated using tables in appendix C. The main costs associated with each of the four cases are listed below with their payback periods

Table 9.1 Comparison of cases

Cost Factor	Case1	Case 2	Case 3	Case 4
Feedstocks (raw materials)	$ 713,500	$ 770,000	$ 712,400	$ 6,070,000
Total Equipment Cost	$ 3,460,000	$ 4,000,000	$ 7,027,500	$ 4,700,000
Total Depreciable Capital	$ 10,000,000	$ 10,600,000	$ 9,654,000	$15,000,000
Operations (labor-related)	$ 450,000	$ 954,000	$ 466,000	$ 3,500,000
Maintenance	$ 1,150,000	$ 1,230,000	$ 1,110,000	$ 1,730,000
Operating Overhead	$ 200,000	$ 277,000	$ 191,430	$ 875,000
Property taxes and insurance	$ 200,000	$ 213,000	$ 193,000	$ 300,000
Depreciation	$ 800,000	$ 850,000	$ 770,000	$ 1,200,000
Cost of manufacture	$ 4,420,000	$ 5,500,000	$ 4,110,000	$ 17,500,000
General expenses	$ 1,160,000	$ 950,000	$ 817,000	$ 2,330,000
Total production cost	$ 5,600,000	$ 6,500,000	$ 5,000,000	$ 20,000,000
Sales Revenue	$12,000,000	$10,000,000	$ 8,550,000	$ 24,400,000
Net Income	$ 6,400,000	$ 3,500,000	$ 3,550,000	$ 4,400,000
Payback period	2.0 years	3.5 years	3.2 years	3.7 years

9.1.2 Sensitivity analysis

The sensitivity of payback period to changes in total depreciable costs, sales, and production cost has been investigated. Each of the three parameters was varied ± 5%, ± 10%, ± 15%, and ± 20%. The total depreciable costs, sales, and production costs for each of the four recycling scenarios are not comparable due to the fact that the different scenarios use different equipment, employ different numbers of operators, and sell different products. Hence, the sensitivity of the payback period to each of the three parameters has been analyzed on an individual basis.

The results for the four cases are as follows.

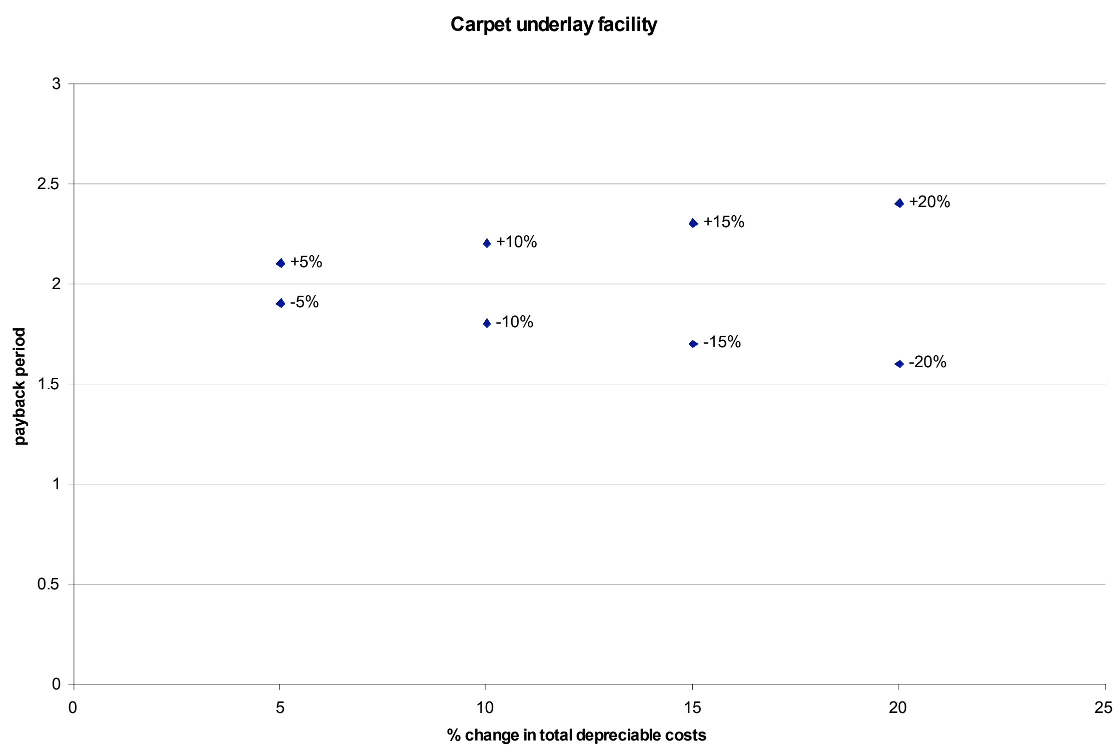

Figure 9.1 Sensitivity of payback period to change in total depreciable costs for the carpet underlay facility

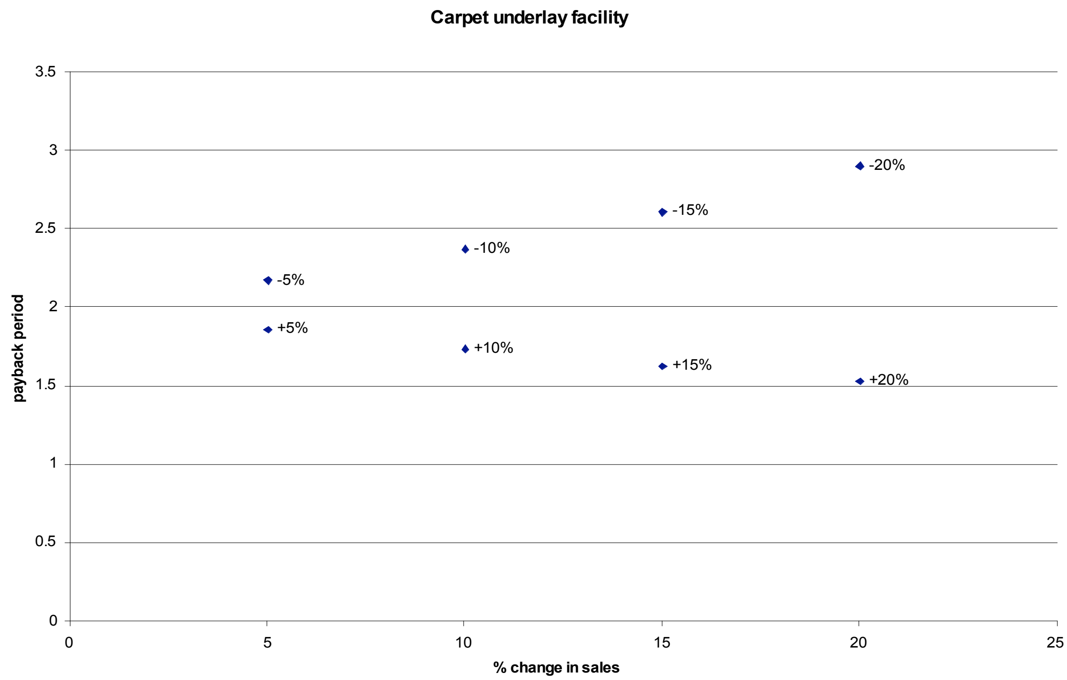

Figure 9.2 Sensitivity of payback period to change in sales for the carpet underlay facility

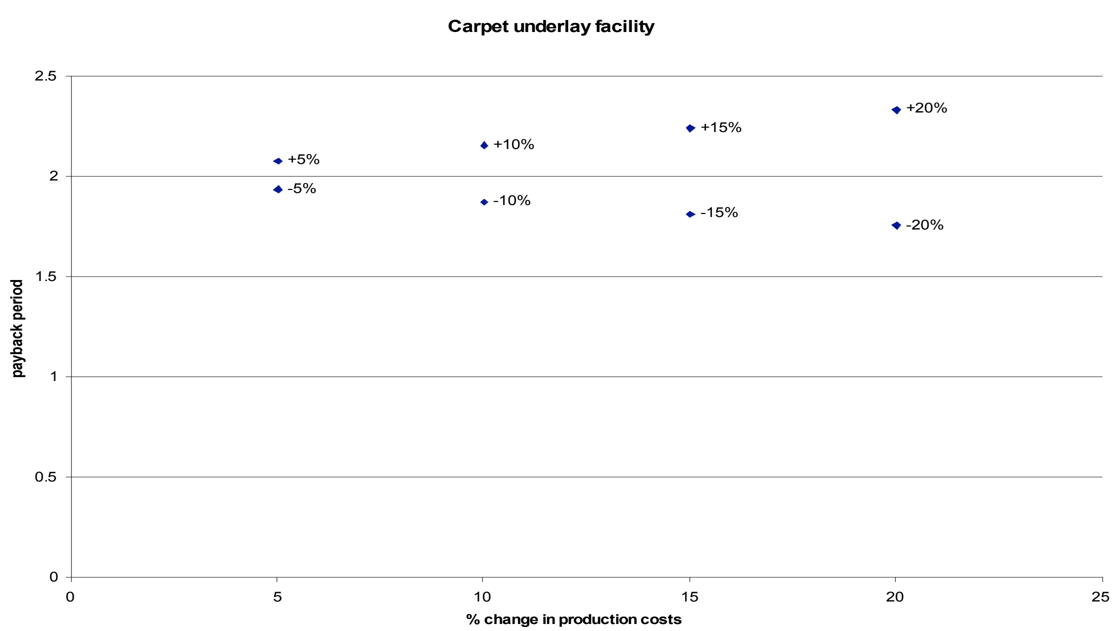

Figure 9.3 Sensitivity of payback period to change in production costs for the carpet underlay facility

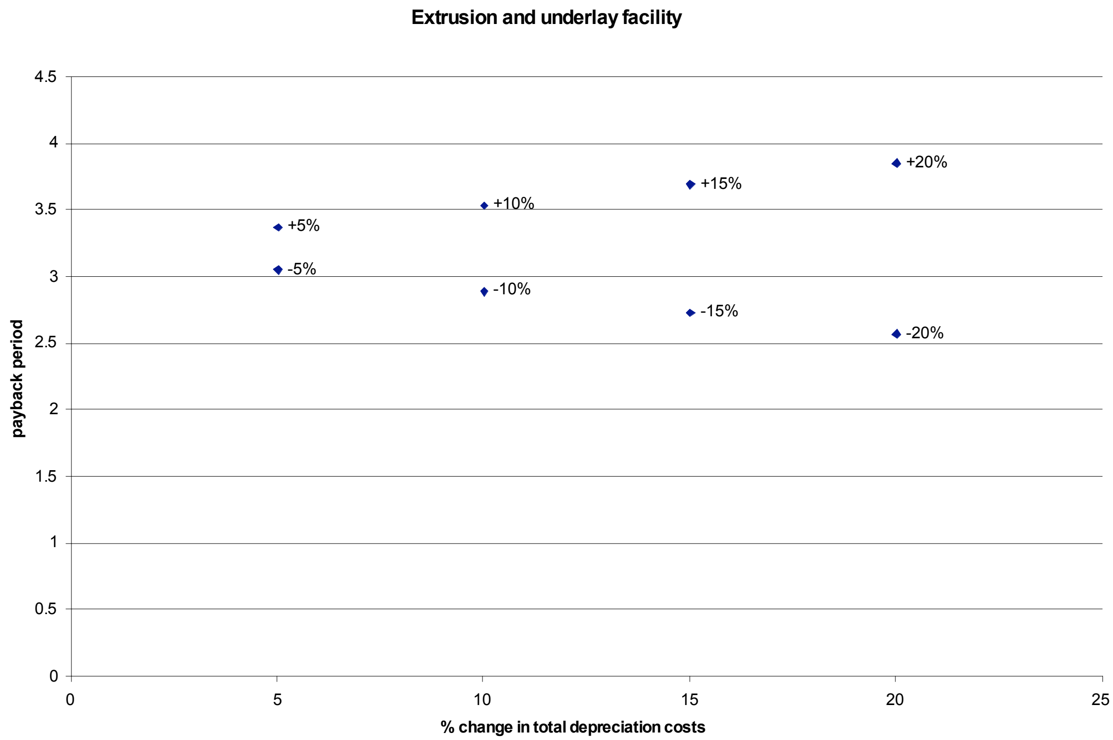

Figure 9.4 Sensitivity of payback period to change in total depreciable costs for the extrusion and underlay facility

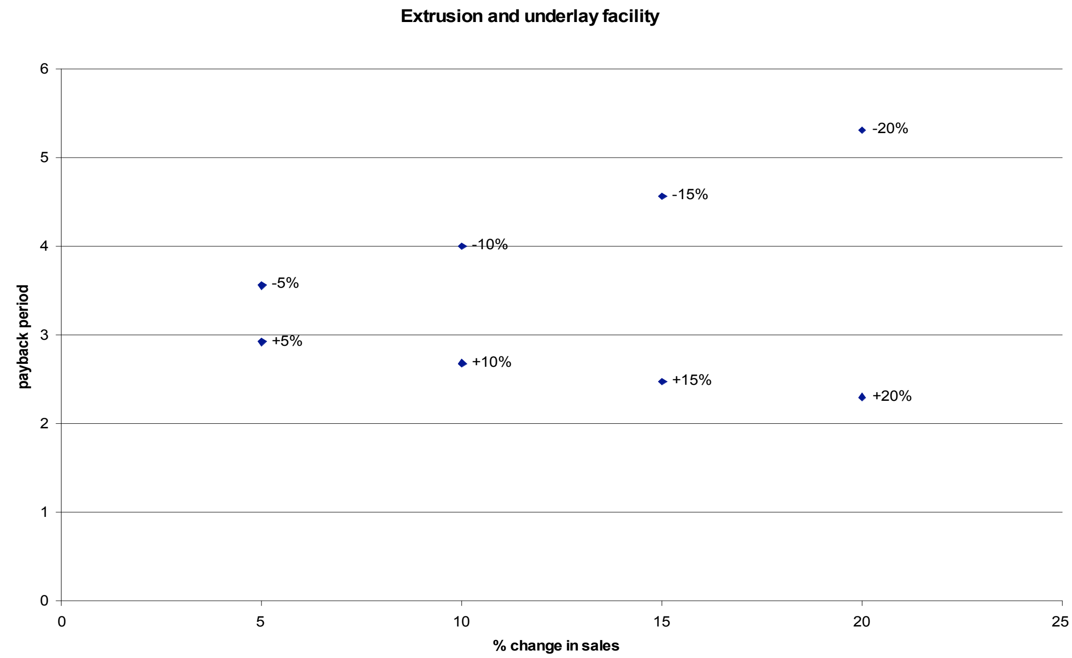

Figure 9.5 Sensitivity of payback period to change in sales for the extrusion and underlay facility

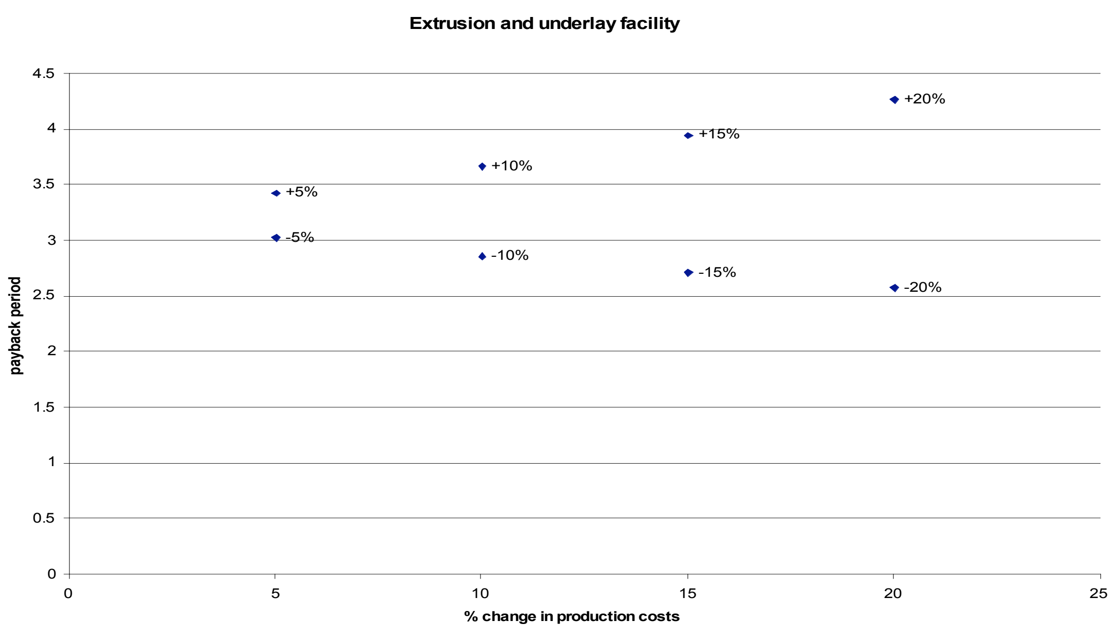

Figure 9.6 Sensitivity of payback period to change in production costs for the extrusion and underlay facility

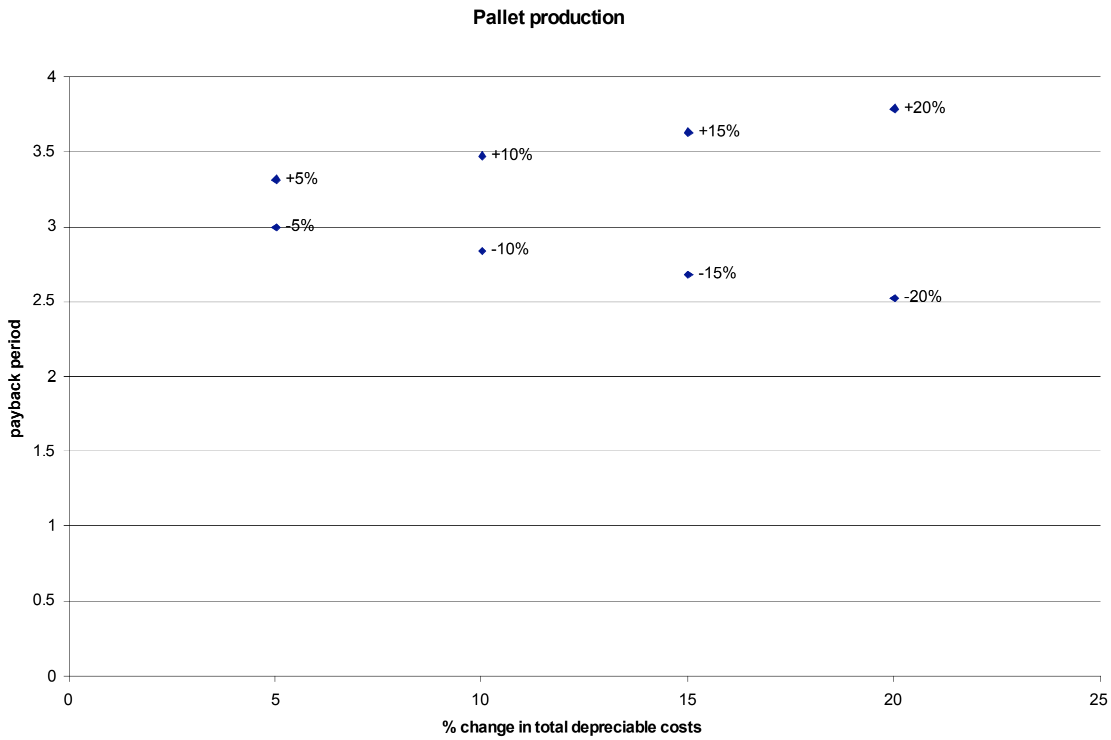

Figure 9.7 Sensitivity of payback period to change in total depreciable costs for the pallet production facility

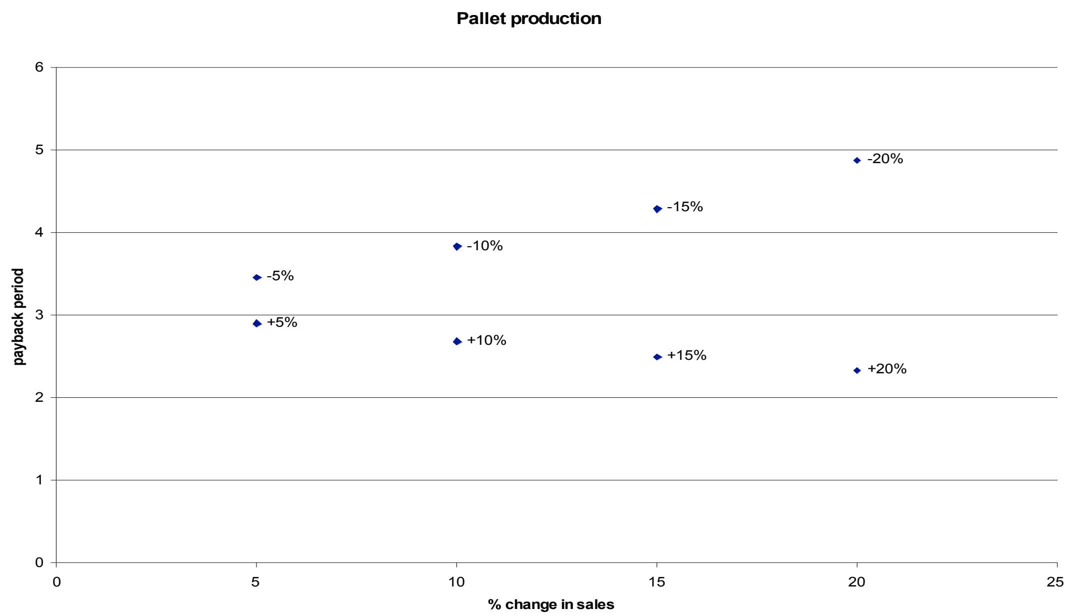

Figure 9.8 Sensitivity of payback period to change in sales for the pallet production facility

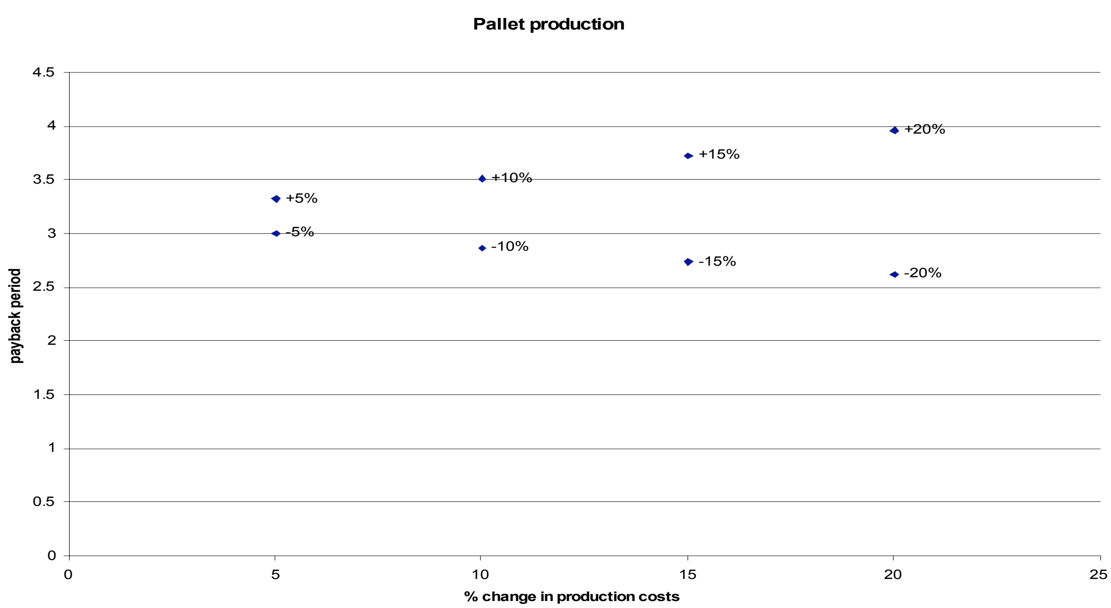

Figure 9.9 Sensitivity of payback period to change in production costs for the pallet production facility

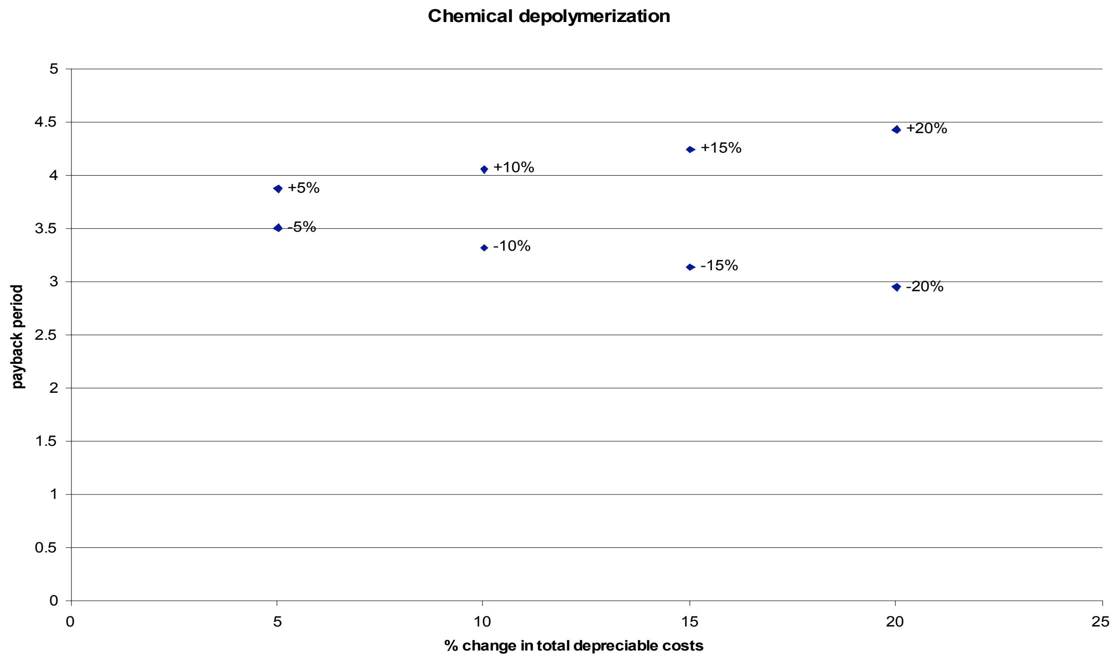

Figure 9.10 Sensitivity of payback period to change in total depreciable costs for the chemical depolymerization facility

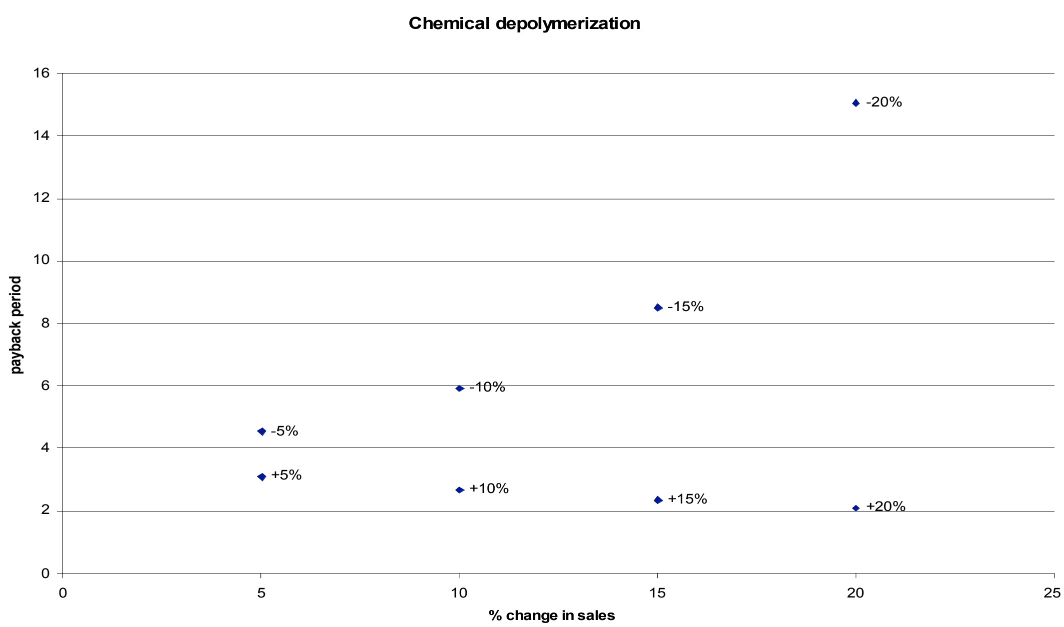

Figure 9.11 Sensitivity of payback period to change in sales for the chemical depolymerization facility

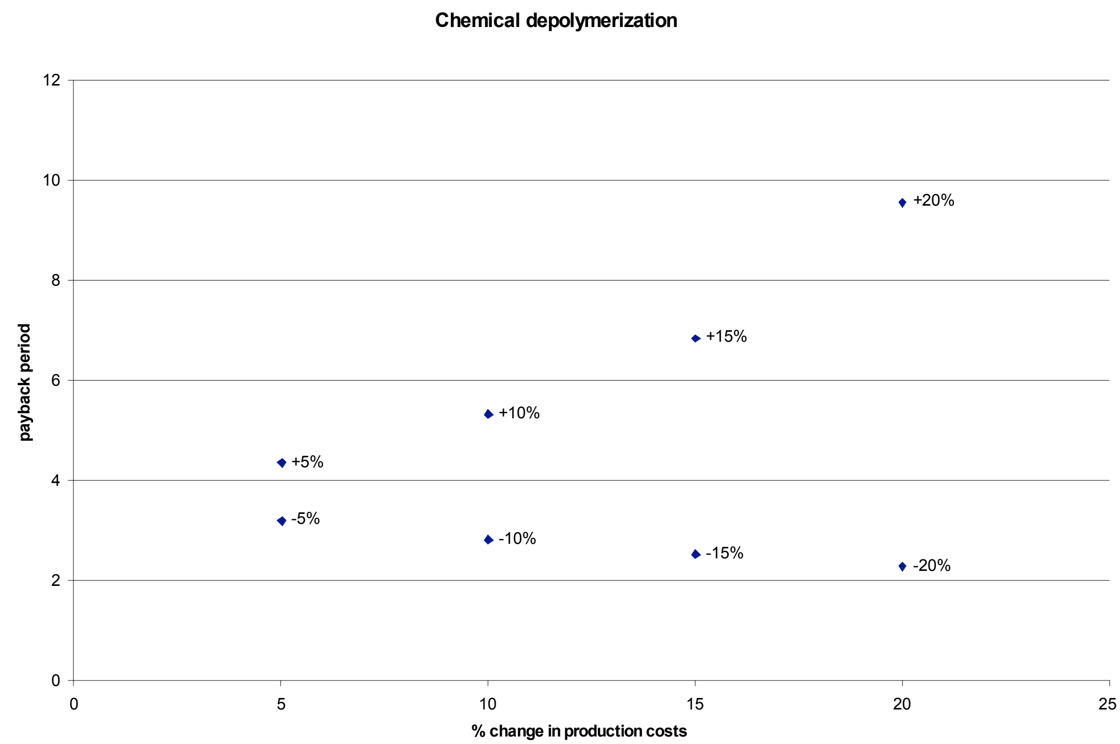

Figure 9.12 Sensitivity of payback period to change in production costs for the chemical depolymerization facility

The figures for each of the four cases show that change in sales affects payback period the most among the three parameters.

9.2 Discussion

9.2.1 Payback periods

The underlay manufacturing facility, case 1, has the lowest payback period and therefore seems most profitable. This is because of the low equipment cost, low labor cost and relatively high selling price of the product. Even though some of the face fiber collected from the carpet may be too short for carding and needle punching, the material throughput is still high because all types of face fibers can be used for this purpose.

The pallet production facility, case 3, the depolymerization using an extruder plus underlay facility, case 2, and the chemical plant, case 4 have similar pay back periods.

The pallet production facility has the second lowest payback period. This facility is environmentally more sustainable because most of the collected carpet including the backing goes into pallet production.

The depolymerization using an extruder plus underlay facility, case 2 is a grave to cradle approach, but only for nylon 6 face fiber. The moderate payback period highlights the lack of significant amounts of nylon 6 material collected. The equipment cost and maintenance is not inexpensive either. Only 25% of carpet collected is nylon 6. Thus the sales figures are not high enough. In reality however, the caprolactam manufacturers would use the produced caprolactam to make in-house nylon 6 for further use in carpets, automotive parts etc. Government subsidies for "green business" ventures may also make this process more profitable.

Case 4, the chemical plant is a medium scale plant as is seen from the investment cost. This is also a hypothetical situation, so there is no way to compare this process with any existing situation. The hypothetical situation, in comparison to the first two processes, does not fair well. In the event of such a plant being set-up for operation other factors such as government subsidies and other "green" business measures may be added motives. This process describes a true grave to cradle approach for both types of nylon.

9.2.2 Reduction in carpet disposal per capita

Current carpet disposal per capita = 2.3 billion kg disposed per yr / 300 million people in USA [51] = 7.7 kg/yr/person

There are 25 metropolitan areas in the United States with populations of 2 million or more [52]. Assume there exists one decentralized facility in each of these areas. However, there would be a far fewer number if the centralized facility because of high capital costs. Assume there are eight centralized facilities in all of the United States.

If case 1/case 2 is in operation,

Carpet disposal per capita = (2.3 billion kg/yr – 25 plants x 4545 kg/hr/plant x 50% recoverable face fibers x 330 days/year x 8 hr/day)/ 300 million people in USA = 7.2 kg/yr/person

If case 3 is in operation,

Carpet disposal per capita = (2.3 billion kg/yr – 25 plants x 4545 kg/hr/plant x 90% usable material x 330 days/year x 8 hr/day)/ 300 million people in USA = 6.7 kg/yr/person

If case 4 is in operation,

Carpet disposal per capita = (2.3 billion kg/yr – 8 plants x 4545 kg/hr/plant x 50% recoverable face fibers x 350 days/year x 24 hr/day)/ 300 million people in USA = 7.2 kg/yr/person

The three decentralized cases are successful in reducing the "carpet footprint" of a person per year. The disposal of carpet per person could potentially reduce to 6.7 kg/yr down from 7.7 kg/yr. Among the three decentralized cases, a low capital investment and a low pay back period makes the pallet production facility/ underlay manufacturing facility more attractive than the depolymerization facility.

CHAPTER 10

CONCLUSIONS AND RECOMMENDATIONS

10.1 Conclusions

As has been seen throughout the carpet recycling industry's history, collection costs are important. The collection costs can be reduced dramatically by having recycling facilities that service each metropolitan area with a population of 2 million people or more. Hence, when collection costs are taken into account, the decentralized cases seem to be most economically viable.

In terms of economic viability measures, such as payback periods, the underlay manufacturing facility has the lowest payback period. Assuming that the 2.3 billion kg of carpet disposed annually gets replaced by the same amount of new carpet, there is a potential in the market for 2.3 billion kg of underlay to be sold. If 25 underlay manufacturing facilities were located all over the US, this would account for the production of 121.5 million kg of environmentally sustainable underlay (5.2% of current production rate in the US).

The world market for shipping pallets is 1.5 billion pallets sold annually with the US alone accounting for 0.5 billion pallets [53]. As mentioned before in chapter 9 if 25 pallet manufacturing facilities were located all over the US, this would account for the production of 24.3 million environmentally sustainable pallets (4.9 % of current production rate in the US). The low investment cost, low labor cost, and high selling price of the product allows for a good payback period making this recycling route attractive.

BASF, DSM, and Honeywell collectively produce 840,000 tonnes of caprolactam annually in the US [54]. Again, if 25 extruder based nylon 6 depolymerization plants with underlay facilities were located all over the US, ~ 28,700 tonnes of caprolactam (3.2% of current production rate in the US) would be produced along with 91 million kg of underlay (4 % of current production rate in the US).

10.2 Recommendations

As petroleum based raw materials become more expensive, landfill space becomes more limited, and new technologies and products emerge, the recycling of post-consumer carpet is due to become a fully developed industrial sector.

In order to meet the MOU goals set forth by CARE, which has been shown in chapter 1, a combination of the discussed techniques of recycling has to be in place, along with other recycling strategies. Some PCC is used in the manufacture of under-hood components in cars, synthetic lumber, composite railroad ties, erosion control products and more. The economic studies on carpet recycling that have been presented in this thesis should be expanded to include various other recycling strategies in order to compare them with each other. An analysis on the best locations and material throughput rates for the various recycling centers should also be investigated. The transportation costs of collecting and transporting post consumer carpet to the recycling centers should also be included in further economic studies of recycling.

In order to depolymerize nylon 6, and nylon 6,6, more revenue should be spent on the research and development of such techniques. Nylon 6,6 does not have a well-developed depolymerization technique that details the kinetics of the reactions that occur, the cost of performing such reactions, and the product yield.

While some commercial carpet recycling options are currently active, there is clearly a need for further research to develop diversified approaches that can recycle all types of fibrous waste collected.

Appendix A

SHREDDER DATA

Heuristic for Size Reduction

I. Damon Dedo (877-582-7800 x 3002) – Granutech-Saturn Systems

An initial step is often Roto-Grind machine model 240 (a single rotor – ram fed machine)
For Shaw Edge trim with a 2 inch screen
10,000 lb/hr @400 hp 0.24 MJ/kg
6,000- 7000 lb/hr @ 300 hp 0.27 MJ/kg
For another facility, with no screen (thus producing 2" to 12" pieces)*
7.5 – 10 tons/hr @ 300 hp 0.12 – 0.09 MJ/kg
The effect of no screen and hence no internal recycle is pronounced
*For this cutting system, with whole carpet the cutters get 70 – 100 hours before these need to be rotated to expose another face, then another 70 – 100 hours before disposal to a steel scrap dealer.

They then use a flat blade size reduction machine, such as the Grizzly model 80

Carpet Throughput, lb/hr	Horsepower, hp	Screen	Specific Energy, MJ/kg
6,000	300	3/8 inch	0.30
7,000	300	½ inch	0.25

From these data we can produce a graph of specific energy versus screen size.
Blade replacement is very infrequent because these can be rotated four times, the sharpened and used again and again. Our main challenge is to understand how pure a nylon face stream we can get as the size reduction becomes smaller.

Balcones (Randy Wolf) uses their Roto Grind and a 2 inch screen with diaper trim and carpet. They get 4-4.5 tons/hr with 300 hp = 0.21 MJ/kg. They also get 1.5 – 2 tons/hr with 150 hp = 0.25 MJ/kg. Damon thought Balcones would bet a higher through put with carpet than the diaper trim. Balcones makes fuel pellets from the diaper/carpet mix.

Ancillary equipment for carpet recycling
Metal Conveyor – 7.5 – 10 hp with throughput equivalent to the size reduction unit
Rubber Conveyor – 1-3 hp with throughput equivalent to the size reduction unit

Vibrating screen for $CaCO_3$ removal into heavies stream
5 hp with equivalent throughput to size reduction machine

II. Doug King, Republic Machine, Inc (502-637-6778)

Their machines are the kind of devices used on whole rolls of carpet and produce large size pieces (average size 1 inch, but many are 2 – 4 inch). The screens are about 2 inch. Baled post consumer carpet is about 5ftx4ftx2.5ft and weighs 1,000 lb for a density of about 20 lb/cu ft. After grinding/shredding the density is about 10 lb/sq ft.

Two machines

Carpet Throughput, lb/hr	Horsepower, hp	Screen	Specific Energy, MJ/kg
5,000	175	2 inch	0.21
10,000	300	2 inch	0.18

As a rough rule of thumb, he felt these machines will have a 10% reduction in specific energy when no screen is present.

Dust suppression energy was estimated to be a cyclone and dust bag needing about 10 hp, while a full pneumatic conveyor plus cyclone and dust bag would need about 30 – 40 hp

Conveyor needs about 5-10 hp at the flow of these shredders.

Knife/cutter replacement for carpet would be at about 2000 tons processed, but that for a 10% greater cost, this could be extended to 8,000 tons.

III. Bob Gilmore, Vecoplan [336-861-6070 (O); 336-210-0961 (cell)]

Their machine is a shredder/cutter and operates with about a 4 inch screen. He felt for this type of machine the minimum screen is 1.5 inch.

Carpet Throughput, lb/hr	Horsepower, hp	Screen	Specific Energy, MJ/kg
6,000 – 8,000	200 (hydraulic drive)	4 inch	0.15 – 0.20
10,000 – 12,000	electromagnetic drive***	4 inch	0.022 – 0.03

*** higher capital cost, but much lower operating electricity needs.

IV. Rick Mc Neil, Cumberland (508-399-3064)

They make granulators and have real experience with carpet. They always require a first stage of shredding before their machines. This is shredding with 1.5 – 2 inch screens. Their large machine will do abut 5,000lb/hr and 3/16 inch screen is about the very lowest you can go with carpet.

Carpet Throughput, lb/hr	Horsepower, hp	Screen	Specific Energy, MJ/kg
5,000	300	5/8	0.35
2,500	300	3/8	0.70
1,000	300	3/16	1.75
5,000	300	3/16****	1.05

**** Three 300 hp machines operating in series with a 5/8 " then 3/8 " then 3/16" screen

Appendix B

PURCHASE COST OF RECIPROCATING PUMPS

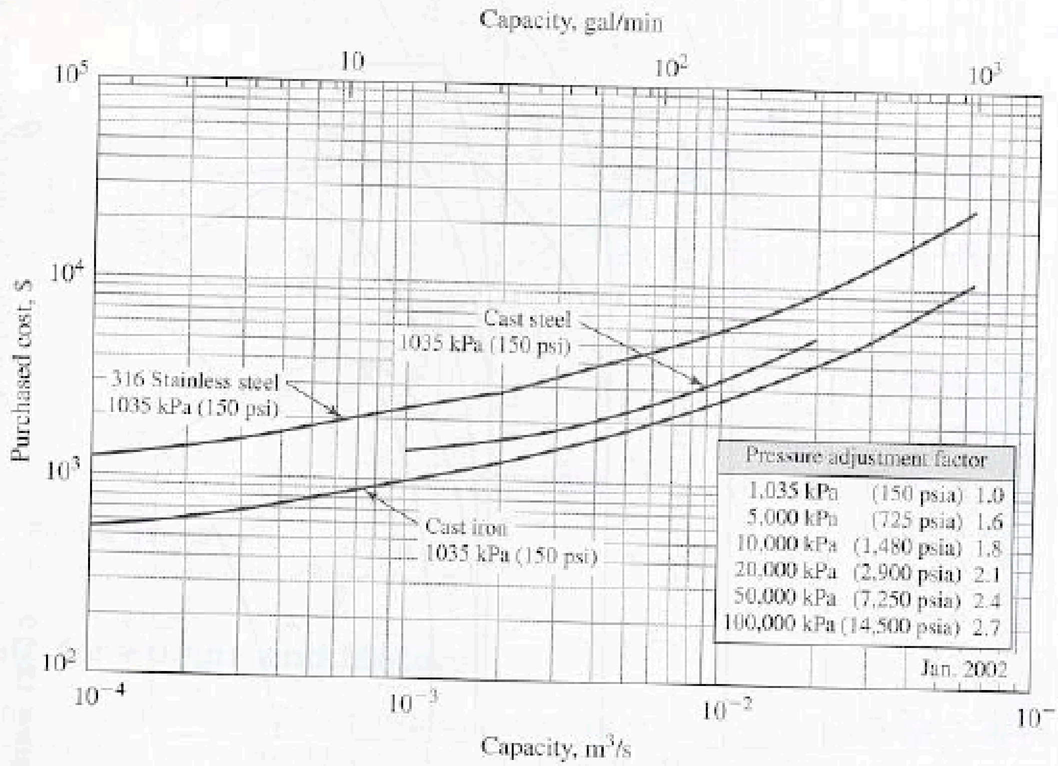

Figure 12-21
Purchased cost of reciprocating pumps. Price includes pump and motor.

Appendix C

EXCEL DATA FOR THE RECYCLING CASES

Carpet Underlay manufacture

Equipment	Power used (HP)	Cost (USD)	Source	Bare Module Factor
Shredder	900	450,000	vendor	1
Agitator	8	8,760	table 16.32	2
Conveyor belt	11	1,014	table 16.32	2
Needle punch	135	1,600,000	vendor	2
Cross Lapper	125	600,000	vendor	2
Card	125	800,000	vendor	2
Total	1,304	5,445,311		

Utilities
Equipment is 85% efficient

Electricity	241,621	USD
Landfill	471,900	USD

Operations (labor-related) (O)		
Direct Wages & Benefits (DW&B)	237,600	USD
Direct Salaries & Benefits (DW&B)	35,640	USD
Operating supplies and services	14,256	USD
Technical assistance to manufacturing	104,000	USD
Control Laboratory	57,000	USD
Maintenance (M)		
Total bare-module costs	5,445,311	USD
Cost of site preparation and service facilities	2,767,819	USD
Cost of contingencies and contractor's fee	1,799,083	USD
Total depreciation costs	10,012,213	USD
Wages and Benefits (MW&B)		
Solid handling process	500,611	USD
Salaries and benefits	125,153	USD
Materials and services	500,611	USD
Maintenance overhead	25,031	USD
Operating overhead		
M&O-SW&B	899,003	USD
General plant overhead	63,829	USD
Mechanical services dept	21,576	USD
Employee relations dept.	53,041	USD
Business services	66,526	USD
Property taxes	200,244	USD
Depreciation	800,977	USD
COST OF MANUFACTURE (COM)	4,418,618	USD

Sales		
Selling price of underlay is $100 for 80 lbs		
Total sales (S)	12,236,400	USD
General Expenses		
Selling (or transfer) expenses	122,364	USD
Direct research	587,347	USD
Allocated research	61,182	USD
Administrative expense	244,728	USD
Management incentive compensation	152,955	USD
Total general expenses (GE)	1,168,576	USD
Total production cost	5,587,195	USD
PBP	2	years

Equipment pricing

- The price and power usage for the shredder are based on estimates given to me by Chris Stzrelecki from Advanced Extrusion Systems.
- The price of the Agitator is calculated using Cost = $2850*S^{0.57}$, where S is the power input of the agitator. I used S = 20 HP based on the power input of cyclone separators.[31a]
- The price of the Conveyor belt is calculated using Cost = 16.9WL, where W is the width and L is the length of the conveyor belt. Based on an approximate size of the facility (50ft by 50 ft), I used W= 72 in and L = 10 ft.[31a]
- The price and power usage of the card, the cross lapper and the needle punch is based on estimates given to me by Terry Purdy from Dilo Group, Germany.

[#] - Equations taken from Chapter 16 of *Product and Process Design Principles* by Seider, Seader and Lewin (SSL).

Utilities

85% efficiency for the equipment is used because some power supplied will be dissipated as heat. The price for electricity used is \$0.08/KWh, representative of the state of Georgia. The landfill costs used are \$32.50/ton waste disposed.

Bare Module Factor (BFM)

Table 16.11 of *Product and Process Design Principles* by Seider, Seader and Lewin (SSL) lists the bare module factors (BMF) for various types of equipment. These take into account the field materials for installation, direct field labor charges, freight charges, contractor engineering expenses, construction overhead etc.

The shredder uses the BMF of a crusher and the agitator uses that of a centrifuge. The horizontal conveyor BMF is given. The needle punch, cross lapper and card are listed as having an BMF of 2 because it would not take too much material and labor to install the pieces bought commercially.

Total bare module costs are calculated by summing the product of equipment cost with the respective BMF.

The **cost of site preparation** include costs for making land surveys, dewatering, drainage, rock blasting, fencing, landscaping etc. Cost for service facilities include utility lines, control rooms, laboratories for feed and product testing, maintenance shops etc. A ratio factor of 0.8 has been used to calculate this amount.

Cost of contingencies and contractor's fee are included to provide for unanticpitated costs incurred during the construction of a plant. A ratio factor of 0.52 has been used to calculate this amount.

The **total depreciable cost (C_{TDC})** is a sum of the total care module costs, the cost of site preparation and service facilities, and cost of contingencies and contractors fees.

The **labor related operations, maintenance, property tax and depreciation** have been calculated based on the guidelines in the cost sheet (Table 17.1 of *Product and Process Design Principles* by SSL). In general, more maintenance work is needed for a facility with mechanical equipment. For instance, blades in the shredder may need to be replaced often.

Sales (S) is based on the selling price of carpet underlay ($100/80lbs) and production per year. A portion of the face fiber retrieved maybe too short for carding and needle punching purposes. Only 90% of 50% of face fiber is fit for making underlay. Collection cost of waste carpet is $0.15/lb.

The **General expenses** and **total cost of production (C)** are also calculated based on the guidelines in the cost sheet (Table 17.1 of *Product and Process Design Principles* by SSL).

The **payback period (PBP)** is the time required for the annual earnings to equal the original investment.

PBP = $C_{TDC}/((1-t)(S-C)+D)$

Where C_{TDC} = total depreciable cost , S = Sales, C = Total cost of production, D = depreciation of direct plant and allocated plant, t = rate of tax

Tax rate is assumed to be 37% annually.

Nylon 6 Depolymerization using twin screw extruder + Underlay Manufacture

Equipment	Power used (HP)	Cost (USD)	Source	Bare module Factor
Shredder	900	450,000	vendor	1
Agitator	8	8,760	SSL	2
Vacuum pump	10	1,300	P&T	1
Conveyor belt	11	1,014	SSL	2
Extruder	228	520,000	SSL	3
Condenser	463	63,750	P&T, vendor	2
Needle punch	135	1,600,000	vendor	2
Cross Lapper	125	600,000	vendor	2
Card	125	800,000	vendor	2
Total	1,620	7,187,499		

Feedstocks (raw materials)

Utilities

Equipment is 85% efficient

Electricity	300,170	USD
Landfill	471,900	USD
Cooling water	79	USD

Operations (labor-related) (O)

Plant runs 330 days/year for one shift of 8 hours/day with 4 operators/shift

Direct Wages & Benefits (DW&B)	316,800	USD
Direct Salaries & Benefits (DW&B)	47,520	USD
Operating supplies and services	19,008	USD
Technical assistance to manufacturing	104,000	USD
Control Laboratory	114,000	USD

Plant runs 330 days/year for one shift of 8 hours/day with 2 operators/shift

Direct Wages & Benefits (DW&B)	158,400	USD
Direct Salaries & Benefits (DW&B)	23,760	USD
Operating supplies and services	9,504	USD
Technical assistance to manufacturing	104,000	USD
Control Laboratory	57,000	USD

Maintenance (M)

Total bare-module costs	7,187,499	USD
Cost of site preparation and service facilities	2,115,859	USD
Cost of contingencies and contractor's fee	1,375,309	USD
Total depreciation costs	10,678,667	USD
Wages and Benefits (MW&B)		
Solid handling process	533,933	USD
Salaries and benefits	133,483	USD
Materials and services	533,933	USD
Maintenance overhead	26,697	USD

Operating overhead

M&O-SW&B	1,213,897	USD
General plant overhead	86,187	USD

Mechanical services dept	29,134	USD
Employee relations dept.	71,620	USD
Business services	89,828	USD
Property taxes	213,573	USD
Depreciation	854,293	USD
COST OF MANUFACTURE (COM)	5,512,720	USD
Sales		
Selling price of caprolactam is $ 0.9 for 1 lb and Selling price of underlay is $100 for 80 lbs		
Total sales (S)	10,423,050	USD
General Expenses		
Selling (or transfer) expenses	104,231	USD
Direct research	500,306	USD
Allocated research	52,115	USD
Administrative expense	208,461	USD
Management incentive compensation	130,288	USD
Total general expenses (GE)	995,401	USD
Total production cost	6,508,121	USD
PBP	3	years

Equipment pricing

- The shredder, and agitator have been modeled using the same guidelines as for previous case.
- The price of the extruder and the power input of the extruder is based on a correlation developed by Dr Muzzy, ChBE, Georgia Tech.
- The price and power usage of the condensor is based on heat exchanger data from Peter and Timmerhaus, and US conveyor solutions in Florida. I also assumed the power usage to be 200 HP based on power usage by air conditioning systems

Utilities is calculated using the same guidelines as for previous case. In this case, 25 gallons per day has been added for the maintenance of condensor.

Bare Module Factor (BMF) has been calculated based on the guidelines in Table 16.11 of *Product and Process Design Principles* by SSL**. Total bare module costs, Cost of site preparation, Cost for service facilities, Allocated costs for utilities and relation facilities, total depreciable cost (C_{TDC}), labor related operations, maintenance, property tax** and **depreciation** have been calculated based on the guidelines in the cost sheet (Table 17.1 of *Product and Process Design Principles* by SSL).

Sales (S) is based on the selling price of caprolactam (~$1/lb) production per year from the 25% of carpet that is Nylon 6and yield of reaction (80%) plus the underlay sales from the rest of the 75% of carpet. $0.15 is the price of collected carpet.

The **General Expenses, total cost of production (C)** and **Payback period (PBP)** are also calculated based on the guidelines in the cost sheet (Table 17.1 of Product and Process Design Principles).

Pallet Production

Equipment	Power used (HP)	Cost (USD)	Source	Bare Module Factor
Shredder	900	450,000	vendor	1
Extruder	1,200	1,124,000	J.Muzzy	2
Compression press+mold	0	2,077,000	J.Muzzy	2
Total	2,100	7,027,500		

Feedstocks (raw materials)		
Utilities		
Equipment is 85% efficient		
Electricity	389,097	USD
Landfill	85,800	USD

Operations (labor-related) (O)		
Plant runs 330 days/year for one shift of 8 hours/day with 3 operators/shift		
Direct Wages & Benefits (DW&B)	252,000	USD
Direct Salaries & Benefits (DW&B)	37,800	USD
Operating supplies and services	15,120	USD
Technical assistance to manufacturing	104,000	USD
Control Laboratory	57,000	USD
Maintenance (M)		
Total bare-module costs	7,027,500	USD
Cost of site preparation and service facilities	1,591,520	USD
Cost of contingencies and contractor's fee	1,034,488	USD
Total depreciation costs	9,653,508	USD
Wages and Benefits (MW&B)		
Solid handling process	482,675	USD
Salaries and benefits	120,669	USD
Materials and services	482,675	USD
Maintenance overhead	24,134	USD
Operating overhead		
M&O-SW&B	893,144	USD
General plant overhead	63,413	USD
Mechanical services dept	21,435	USD
Employee relations dept.	52,696	USD
Business services	66,093	USD
Propert taxes	66,093	USD
Depreciation	193,070	USD
COST OF MANUFACTURE (COM)	4,113,103	USD
Sales		
Selling price of pallets is $0.73/lb		
Total sales (S)	8,553,600	USD
General Expenses		
Selling (or transfer) expenses	85,536	USD

Direct research	410,573	USD
Allocated research	42,768	USD
Administrative expense	171,072	USD
Management incentive compensation	106,920	USD
Total general expenses (GE)	816,869	USD
Total production cost	4,929,972	USD
PBP	3	years

Equipment pricing

- The shredder has been modeled using the same guidelines as for previous case.
- The price of the extruder, compression press + mold and their power input are based on a correlation provided by Dr Muzzy, ChBE, Georgia Tech.

Utilities are calculated using the same guidelines as for previous case.

Bare Module Factor (BMF) has been calculated based on the guidelines in Table 16.11 of *Product and Process Design Principles* by SSL**. Total bare module costs, Cost of site preparation, Cost for service facilities, Allocated costs for utilities and relation facilities, total depreciable cost (C_{TDC}), labor related operations, maintenance, property tax** and **depreciation** have been calculated based on the guidelines in the cost sheet (Table 17.1 of *Product and Process Design Principles* by SSL).

Sales (S) is based on the selling price of shipping pallets (~\$0.7/lb). The price of collected carpet is \$0.15.

The **General Expenses, total cost of production (C)** and **Payback period (PBP)** are also calculated based on the guidelines in the cost sheet (Table 17.1 of Product and Process Design Principles).

Nylon 6,6 and Nylon 6 depolymerization using chemical means

Equipment	Power used	Cost (USD)	Source	Bare Module Factor
Shredder	900	450,000	vendor	1
Extruder	336	623,500	Muzzy	3
Hydrolyzer	6,550	50,330	SSL	4
Filter	0	100,000	SSL	3
Crystallizer	2,700	99,150	SSL	3
Centrifuge	50	240,000	SSL	2
Dryer	150	10,000	SSL	2
Storage	0	3,700	SSL	2
Wastewater treatment	1	117,000	SSL	3
Agitator	8	8,760	SSL	2
Needle punch	135	1,600,000	vendor	2
Cross Lapper	125	600,000	vendor	2
Card	125	800,000	vendor	2
Total	10,688	8,832,904		

Feedstocks (raw materials)
Utilities
Equipment is 85% efficient

Electricity	1,884,386	USD
Steam	235,464	USD
Natural gas	153,900	USD
Fuel Oil	1,230,216	USD
Landfill	1,314,000	USD
Wastewater treatment	1,250,000	USD

Operations (labor-related) (O)
Plant runs 350 days/year for 3 shifts of 8 hours/day with 10 operators/shift

Direct Wages & Benefits (DW&B)	2,520,000	USD
Direct Salaries & Benefits (DW&B)	378,000	USD
Operating supplies and services	151,200	USD
Technical assistance to manufacturing	208,000	USD
Control Laboratory	228,000	USD

Maintenance (M)

Total bare-module costs	8,832,904	USD
Cost of site preparation and service facilities	3,762,352	USD
Cost of contingencies and contractor's fee	2,445,529	USD
Total depreciation costs	15,040,785	USD
Wages and Benefits (MW&B)		
Solid handling process	752,039	USD
Salaries and benefits	188,010	USD
Materials and services	752,039	USD
Maintenance overhead	37,602	USD

Operating overhead		
M&O-SW&B	3,838,049	USD
General plant overhead	272,501	USD
Mechanical services dept	92,113	USD
Employee relations dept.	226,445	USD
Business services	284,016	USD
Property taxes	300,816	USD
Depreciation	1,203,263	USD
COST OF MANUFACTURE (COM)	17,500,058	USD
Sales		
Selling price of caprolactam, adipic acid, hexamethylene diamine is $0.9 for 1 lb		
Total sales (S)	24,377,220	USD
General Expenses		
Selling (or transfer) expenses	243,772	USD
Direct research	1,170,107	USD
Allocated research	121,886	USD
Administrative expense	487,544	USD
Management incentive compensation	304,715	USD
Total general expenses (GE)	2,328,025	USD
Total production cost	19,828,083	USD
PBP	**4**	**years**

Equipment pricing

- The price of a vertical cylindrical hydrolyser, $C_p = F_M C_V + C_{PL}$, where C_V is the cost of the empty vessel, including nozzles, manholes, and supports, and C_{PL} is the cost of platforms and ladders has been obtained from [31a].The power usage is an estimate based on the heat duty of material.
- The power usage and the cost of the extruder have been obtained from J.Muzzy
- The price of a continuous filter system has been obtained from Figure 15.39 in chapter 15, separation equipment, of Peter and Timerhaus.
- The price and power usage of the crystallizer is calculated using

#Cost =27,500$W^{0.56}$, where W is the tons of material processed per day. The allowed range of W is 10 – 1,000 ton/day. [31a]

- The price and power usage of the centrifuge is calculated using #Cost = =47,000$S^{0.30}$, where S is the tons of material processed per hr. The allowed range of S is 2-40 ton/hr. [31a]
- The price of a tumble dryer has been taken from [32c] based on the area required to dry the material. The power required depends on the heat duty required to evaporate the water. [31a]
- The price of the storage drums is calculated using drums of volume 0.23 m^3 needed to store a week's yield of product from the facility. [44]
- The price and power usage of the wastewater treatment plant is calculated using
  #Cost = =11,700$Q^{0.64}$, where Q is GPM of water processed. [31a]

Utilities is calculated differently in this case. The total power usage for running the equipment has been divided into 4 parts with each part supplied by a different energy source such as electricity, steam, natural gas and fuel oil. Wastewater treatment costs and landfill costs are also added. The price for these utilities is taken from table 17.1 of Product and Process Design Principles with the exception of electricity and landfill costs which are $0.08/KWh and $32.50/ton respectively.

Bare Module Factor (BFM) has been calculated based on the guidelines in Table 16.11 of Product and Process Design Principles. **Total bare module costs, Cost of**

site preparation, Cost for service facilities, Allocated costs for utilities and relation facilities, total depreciable cost (C_{TDC}), labor related operations, maintenance, property tax and **depreciation** have been calculated based on the guidelines in the cost sheet (Table 17.1 of Product and Process Design Principles).

Sales (S) is based on the selling price of caprolactam, adipic acid and hexamethylene diamine (~$0.90/lb), production per year and yield of reaction (90%). The collection costs of waste carpet is $0.15/lb.

The **General Expenses , total cost of production (C)** and **Payback period (PBP)** are also calculated based on the guidelines in the cost sheet (Table 17.1 *of Product and Process Design Principles*).

Appendix D

SUMMARY OF RESULTS

Inputs (units)				Output (units)		
			Carpet Underlay Mfr.			
Process Sequence:				Environmental Impact		
Shredder						
Air separator				Solid Waste	7,139,286	kg/yr
Conveyor belt						
Needle punch						
Cross Lapper						
Card						
				Economic Impact		
Material:						
Sorted, shredded PCC	11,998,800	kg/yr		Underlay sold	12,236,400	$/yr
					133,503	# rolls/yr
Utilities:					36	kg/roll
Electricity	2,568,252	kWh/yr		Profits	6,649,205	$/yr
				Income Tax	2,460,206	$/yr
Labor:				Wages + FB	1,599,901	$/yr
Operating labor	3.00	#/hr		Property Taxes	200,244	$/yr
Supervision	0.25	#/hr		Electricity	205,460	$/yr
Lab tech	0.25	#/hr		Specific Energy	0.21	kWh/kg PCC
Overhead	3.45	#/hr				
Admin	0.35	#/hr				
selling	0.85	#/hr				
R & D	0.45	#/hr				
	8.60	#/hr		Social Costs		
				Employees	8.60	#/hr
Costs				PCC used	11,998,800	kg/yr
Sorted, shredded PCC	0.15	$/lb				
Electricity	0.08	$/kWh				
Operating labor	237,600	$/yr				
Supervision	23,760	$/yr				

Inputs (units)			Depolymerization of nylon 6 in an extruder + underlay manufacturing	Output (units)		
Process Sequence:				Environmental Impact		
Shredder						
Agitator				Solid Waste	7,206,779	kg/yr
Extruder						
Condenser						
Card						
Cross Lapper						
Needle Punch				Economic Impact		
Conveyor						
				Caprolactam sold	1,716,660	$/yr
Material:				Underlay sold	8,259,570	$/yr
Sorted, shredded PCC	11,998,800	kg/yr		Profits	3,914,929	$/yr
KOH catalyst	42,000	kg/yr		Income Tax	1,448,524	$/yr
				Wages + FB	2,182,039	$/yr
Utilities:				Property Taxes	213,573	$/yr
Electricity	3,190,595	kWh/yr		Electricity	255,248	$/yr
Cooling water	1,584,000	gal/yr		Specific Energy	0.27	kWh/kg PCC
Labor						
Operating labor	6.00	#/hr				
Supervision	0.50	#/hr				
Lab tech	0.50	#/hr		Social Costs		
Overhead	6.90	#/hr		Employees	17	#/hr
Admin	0.70	#/hr		PCC used	11,998,800	kg/yr
selling	1.70	#/hr				
R & D	0.90	#/hr				
	17.20	#/hr				
Costs						
Sorted, shredded PCC	0.15	$/lb				
Electricity	0.08	$/kWh				
Operating labor	475,200	$/yr				
Supervision	47,520	$/yr				

Inputs (units)		
Process Sequence:		
Shredder		
Hydrolyzer		
Crystallizer		
pumps		
Centrifuge		
Dryer		
Storage		
Wastewater treatment		
Needle punch		
Cross Lapper		
Card		
Material:		
Sorted, shredded PCC	38,178,000	kg/yr
Utilities:		
Electricity	66,885,504	kWh/yr
Steam	235,464	$/yr
Natural gas	153,900	$/yr
Fuel Oil	1,230,216	$/yr
Labor		
Operating labor	10	#/yr
Supervision	0.83	#/yr
Lab tech	0.83	#/yr
Overhead	11.50	#/yr
Admin	1.17	#/yr
selling	2.83	#/yr
R & D	1.50	#/yr
	29	#/yr
Costs		
Sorted, shredded PCC	0.15	$/lb
Electricity	0.08	$/kWh
Operating labor	2,520,000	$/yr
Supervision	252,000	$/yr

Depolymerization of nylon 6 and nylon 6,6

Output (units)		
Environmental Impact		
Solid Waste	25,550,627	kg/yr
Economic Impact		
Caprolactam sold	4,658,850	$/yr
salt of HMDA and Adipic Acid sold	7,454,160	$/yr
Underlay sold	12,264,210	$/yr
Profits	4,549,137	$/yr
Income Tax	1,683,181	$/yr
Wages + FB	5,214,890	$/yr
Property Taxes	300,816	$/yr
Electricity	5,350,840	$/yr
Specific Energy	1.75	kWh/kg PCC
Social Costs		
Employees	29	#/hr
PCC used	38,178,000	kg/yr

Inputs (units)				Output (units)		
			Pallet production			
Process Sequence:				Environmental Impact		
Shredder						
Extruder				Solid Waste	1,199,880	kg/yr
Compression molding press						
				Economic Impact		
Material:						
Sorted, shredded PCC	11,998,800	kg/yr		Pallets sold	8,553,600	$/yr
					863,914	# pallets/yr
Utilities:					13	kg/pallet
Electricity	4,135,824	kWh/yr		Profits	3,623,628	$/yr
Glass Fiber	2,429,757	kg/yr		Income Tax	1,340,742	$/yr
				Wages + FB	1,576,073	$/yr
Labor				Property Taxes	193,070	$/yr
Operating labor	3.00	#/hr		Electricity	330,866	$/yr
Supervision	0.25	#/hr		Specific Energy	0.34	kWh/kg PCC
Lab tech	0.25	#/hr				
Overhead	3.45	#/hr				
Admin	0.35	#/hr				
selling	0.85	#/hr				
R & D	0.45	#/hr		Social Costs		
	8.60	#/hr		Employees	9	#/hr
Costs				PCC used	11,998,800	kg/yr
Sorted, shredded PCC	0.15	$/lb				
Electricity	0.08	$/kWh				
Operating labor	237,600	$/yr				
Supervision	23,760	$/yr				

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