The Design of a Lean Automobile Dismantling and Recycling System

by

Dean A. Sheppard
S.B. Mechanical Engineering
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Signature of Author .....
System Design and Management Program and
Department of Mechanical Engineering

Certified by .....
David S. Cochran
Assistant Professor of Mechanical Engineering
Thesis Supervisor

Accepted by .....
John R. Williams
Co-Director, System Design and Management Program

Accepted by .....
Ain A. Sonin
Chairperson, Department Committee on Graduate Students

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I would like thank my brothers, Gord, Phil, and Mike for providing me with the information necessary to complete this project and helping me understand and characterize the system. Additionally, without Gord's assistance on the tests in Kansas City, St. Louis, and Calgary, none of this would have been possible.

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Dean.
Have a nice day.

Abstract

The purpose of this project was to design a new, more efficient automobile recycling system for the JMS consortium. JMS is a consortium of 18 independent automobile recycling facilities processing a collective annual throughout of over 200,000 vehicles.

To begin the design process three JMS facilities were studied to establish the system requirements. Based on the requirements a new system was designed using the principles of lean production. Aspects of the system were tested at the same three locations to validate the design.

Based on the test results, the lean system design presented herein is expected to increase effective daily throughput 25%, increase the peak throughput rate by 67%, significantly reduce the handling and therefore damage of each vehicle, and reduce the amount of land allocated to non-value adding buffers by 66%. Furthermore, the lean system is balanced and synchronized to the vehicle-arrival process, with increased volume flexibility. Currently, JMS anticipates implementing the design in all new facilities beginning with the Denver project this month.

To address the question of what is the optimal throughput rate for JMS facilities, all known profit-influencing variables were parameterized and an analytical model of the profit was established. Using some simplifying assumptions, the profit-maximizing throughput was obtained. From this, three interesting and intuitive results were obtained:

1. if there is a profit to be made per vehicle excluding parts-sales then the profit maximizing throughput quantity is infinitely large,
2. if the net loss per vehicle excluding parts sales is less than the maximum potential revenue from parts-sales then a unique optimal throughput exists and should be sought, and
3. if the net loss per vehicle excluding parts-sales is greater than the maximum potential revenues from parts-sales then no throughput will produce profits.

While the work presented in this thesis offers some clear direction in terms of the operation of the recycling system and its throughput quantity, the consortium and indeed the industry will benefit from further work in several areas. The first is to expand the scope of the system design presented in this thesis. The second is, following implementation, to further refine the system for improvements in efficiency. Finally, the analytical model may be expanded to include more complex effects as well as empirical estimates of the parameter values.

Author: Dean Sheppard
Supervisor: Professor David Cochran
Date: September 1998

Table of Contents

Section 1 Introduction

JMS[1] is a consortium of automobile recycling facilities located throughout Canada and the United States. For JMS, automobile recycling includes both the sales of used parts from the automobiles being recycled to retail and commercial customers as well as the separation, preparation, and subsequent sale of recyclable material recovered from the automobiles. Retail customers locate and remove their own parts from the stock of automobiles on hand while JMS staff locate and remove parts sold to commercial customers. Commercial are limited to those who purchase the parts with the intent of repairing and/or rebuilding the parts for subsequent sale to their own clientele.

JMS currently owns and operates 15 facilities and plans to open new facilities at a rate of 4 per year. Annual throughput ranges between 6,000 and 20,000 vehicles per facility with a mean of 10,000 vehicles. Each facility operates as an individual entity and is responsible for all aspects of its business process. These include marketing, used-parts sales, accounting, staffing, as well as completely processing automobiles. In this context, automobile processing is defined by the following steps:

1. Purchasing the automobiles,
2. Making the automobiles available for customer access,
3. Recovering and separating material,
4. Crushing the automobiles.

Although the operations required to recycle a vehicle are nearly identical at all facilities, each facility essentially employs a unique recycling system. The uniqueness of each process may be attributed to the history those facilities.

Early facilities were subject to rapid business growth and then stabilization combined with evolving corporate objectives (throughout the growth phase, revenue contributions from crushed vehicles and used-parts sales shifted relative to each other). In response to these conditions, the recycling systems used at older facilities evolved as patchworks of local process-fixes designed to address the problem at hand with minimal interruption to productivity. More recent facilities, however, have been testing grounds for new ideas. Thus, each of the new facilities employs an essentially unique process resulting from a "trial and error" search for the "best way."

However, with a collective annual throughput over 200,000 vehicles per year, the JMS consortium members felt that a newly designed recycling process based on a sound design methodology with clear objectives was warranted. This project, therefore, was to design a new recycling process for the JMS facilities that would meet or increase the current productivity with fewer resources. The principles of Lean Production were adopted to meet this objective.

A lean system is well suited to JMS facilities as it does not require large capital investments, it is effective over a large range of production volumes, and it encourages continuous improvement. To establish the requirements of the system three JMS facilities were studied: Calgary, Alberta; Kansas City, Missouri; and St. Louis, Missouri. A new design consistent with the requirements was developed and tests to validate aspects of the design were performed at each of the three sites. Although all three locations were used, the bulk of the effort was at the Calgary facility.

Section 2 of this thesis establishes the context in which the design activities took place—effectively, the design space. Through a brief history of Lean Production, Section 3 describes the methodology as well as how it relates to the JMS operations. Section 4 is a comprehensive

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[1] The name has been changed maintain the anonymity of the firm.

and detailed description of the recycling process employed at the Calgary facility including the tools used, their staffing policy, and a productivity summary. Section 4 ends with a discussion of the key deficiencies in the Calgary system. The lean system and the tools designed to support the system are described in Section 5. Section 5 also demonstrates how the lean design is consistent with the Lean Production System Design Decomposition developed by Professor David Cochran of the Production System Design Lab at MIT. The performance results acquired during testing of the system are provided as design validation. Section 5 concludes with a discussion comparing the lean system to the current system in the Calgary facility. Although the lean system attempts to recycle vehicles as efficiently as possible, it does not determine the optimal number of vehicles to recycle per year. Thus, Section 6 presents an analytical model to help answer this question. Although still purely an academic tool, the model is presented here as a matter of completeness. Section 7 suggests potential areas of future research and the information desired from that research. Concluding remarks are provided in the Section 8, the final Section.

Section 2 Project Design Space

JMS facilities purchase and recycle automobiles, their parts, and any additional materials. What follows describes the lifecycle of an automobile in the Calgary facility to establish the design space. All of the steps described below are considered JMS recycling system requirements. Then the scope of this thesis project is established within the lifecycle. The system requirements for this project are, therefore, a subset of the total set of requirements.

JMS receives vehicles from three primary sources: private individuals who sell their vehicles, independent tow-truck drivers who purchase vehicles for the purpose of reselling them to automobile recyclers at a profit, and vehicles acquired through charitable donation programs. Excepting vehicles acquired through charitable donation programs, the amount paid for vehicles is a function of the vehicle's weight and condition. Vehicles acquired through donation programs are done so on a flat rate basis.

Vehicles arrive at JMS facilities randomly throughout the day with lunchtime and early afternoon having the highest arrival frequencies (i.e. the lowest inter-arrival times) as shown in Figure 2-1.[2] However, for this project, the distribution of arrival frequencies is assumed to be constant throughout the day.

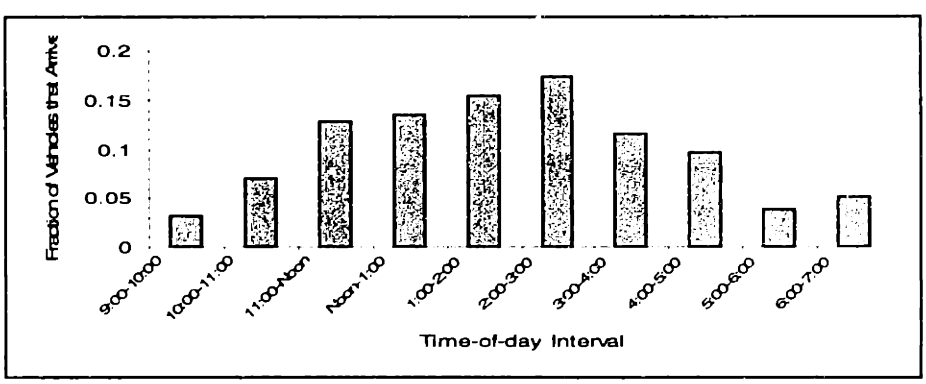

Figure 2-1. Plot of arrival frequencies through the day at the Calgary facility.

[2] Raw data is provided in Appendix A.

All vehicles are categorized by make as one of four types: 1) General Motors products, 2) Ford Motor Company products, 3) Chrysler Corporation and other domestic products (e.g Studebaker), and 4) imported vehicles (e.g. Toyota, Nissan, BMW, etc). The make of any arriving vehicle is assumed to be a random, four parameter, multinomial variable with the liklihoods shown in Figure 2-2 below.

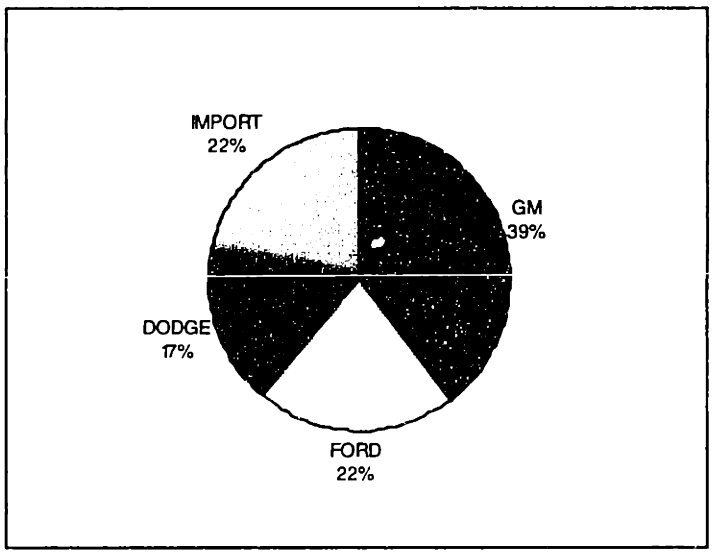

Figure 2-2. Vehicle breakdown by type at the Calgary facility.

Upon arrival, each vehicle is inspected by a purchasing agent and assigned a vehicle number. The next requirement for vehicles is that phase one of the recycling process be completed in the fluid recovery center. Phase one of the recycling process requires that the following fluids be recovered from each vehicle for subsequent processing:

- Engine coolant,
- Engine oil,
- Transmission oil,
- Differential gear oil,
- Power steering fluid,
- Brake fluid,

- Windshield washer fluid,
- Air conditioning Freon, and
- Fuel.

In addition to fluid recovery, phase one also includes removing any garbage from the vehicle interior and trunk, removing the jack, sufficiently damaging the trunk latch mechanism so that it is unable to latch closed and removing the oil filter. With phase one completed, vehicles may be made available for parts without the threat of fluids and garbage contaminating the site.

All parts sales at JMS facilities are on a self-serve basis. That is to say that following phase one, vehicles are placed in rows in the *Parts-Yard* where retail customers may identify and remove any parts they desire. Vehicles in the parts-yard are separated by type: General Motors products, Ford Motor Company products, Chrysler Corporation and other domestic products, and imported vehicles.

The amount of time that vehicles are available for parts is determined by the ratio of the number of parts-vehicles on site to the rate at which vehicles are purchased. During the time that vehicles are available for parts revenues are being generated. Thus, for the purposes of this project, parts availability is considered a value-adding process. Once the time allotted for parts sales has passed, vehicles enter phase 2 of the recycling process.

Phase 2 requires that the following parts, if not yet sold, be removed from the vehicle:

- Alternator,
- Starter,
- Air-conditioning compressor,
- Radiator,

- Fuel tank, and
- Catalytic converter.

Finally, each four vehicles are crushed into a single package and then stored until sold.

As mentioned, the goal of this thesis project was to design a new and more efficient (in terms of throughput and required resources) vehicle recycling process. The system boundaries were established at the scale and the parts-yard exit. Material enters the system from the scale and exits the system ready to be crushed. The system requirements described above were taken to be non-negotiable. Secondary handling of material[3] was considered beyond the scope of this project however, when appropriate, suggestions are made to improve the efficiency of these operations.

[3] Secondary handling is considered to be handling of materials after removed from vehicles. For example, disposal of trash and fluids once removed from the vehicles is considered secondary handling.

Section 3 Relating Lean Production to Automobile Recycling

Following World War II, "[the Toyota Motor Company] was determined to go into full-scale car and commercial truck manufacturing, but it faced a host of problems."[4] Unlike the U.S. market at the time, the Japanese domestic market was small in terms of volume but broad in terms of the types of products demanded. Moreover, the Japanese economy in the post-war years was capital starved making large investments in the most recent western technologies impossible. Under these conditions, Toyota's chief production engineer, Taiichi Ohno, concluded that the mass production methods used in the United States would never succeed in Japan.[5]

The mass production system used in the post-war U.S. automobile plants relied on large lot sizes from high-production-rate machines to overcome the delays caused by long change-over times. For example, to make-up the eight (or more) hours lost during a die change in a sheet metal stamping press, U.S. automobile producers would run a large lot of one part before changing the dies to another part type. Indeed, it was not uncommon for a plant to accumulate three months worth of inventory before changing part types. Producing large lot sizes from very fast, and therefore expensive, machines was not an alternative for Japanese automobile producers. Thus, during the 1940's and 1950's Ohno developed a method for rapidly changing the dies of a stamping press.

"By the late 1950's, [Ohno] had reduced the time required to change dies from a day to an astonishing three minutes and eliminated the need for die-change specialists."[6] The method, termed Single Minute Exchange of Dies (SMED), permitted Toyota to produce small quantities

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[4] James P Womack, Daniel T. Jones, and Daniel Roos, *The Machine that Changed the World:the story of lean production*, New York: Harper Collins, 1990, p49.

[5] This material is based heavily on James P Womack, Daniel T. Jones, and Daniel Roos, *The Machine that Changed the World:the story of lean production*, New York: Harper Collins, 1990.

of each part with frequent die changes. This allowed Toyota to produce small lots of parts in the order they are needed at the rate at which they are needed thereby eliminating the need to carry large inventories. In the process, Ohno also discovered that small lot sizes reduced manufacturing costs in several ways.

First, and most obvious, small lot sizes reduced inventory-holding costs. Second, by holding less inventory the damage incurred through storage and handling was reduced. Finally, Ohno discovered that small lot sizes reduced the fraction of defective parts (i.e. improved the production yield). With large lot sizes, parts may be stored for as much as three months before use. Thus, production defects are not discovered until long after the parts are produced making it difficult to identify the source of the defects. With small lot sizes, however, a defect is discovered soon after the part is produced, often within the same shift, making it possible to identify and correct the cause of the defect. Moreover, by providing timely feedback to the machine operators, the operators were able to learn how to avoid making defective parts in the future. Discovering and exploiting this phenomenon led to a paradigm-shift change in the management of manufacturing processes for Toyota:

> *"Japanese firms ... saw the challenges of manufacturing differently. They realized that eliminating delays in the production process was the key to reducing instability and improving cost, productivity, and service."*[7]

This led to the key tenet of Lean Production: the elimination of waste.

Waste in a manufacturing setting refers to any activity that does not add value. Lean Production defines seven sources of waste in the manufacturing plant:[8]

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[6] James P Womack, Daniel T. Jones, and Daniel Roos, *The Machine that Changed the World:the story of lean production*. New York: HarperCollins, 1990, p53.
[7] Peter M. Senge, *The Leader's New Work: Building Learning Organizations, The Slaon Management Review*, Cambridge: MIT Press, 1990, p8.

1. Overproduction waste is to produce more than demanded or produce it before it is needed. It is visible as stored inventory.
2. Work in Process (WIP) waste refers to material stored between operations as a result of producing parts in large lots. This is often due to operations with long set-up times or very slow cycle times.
3. Transportation waste refers to transporting parts and/or inventory from one location to another. This occurs when subsequent operations are not located near each other or excess WIP (from producing large lots) is transported to some storage location.
4. Processing waste is any processing step or operation that is performed unnecessarily.
5. Motion waste refers to unnecessary motion of workers while performing operations.
6. Waiting waste occurs when one worker must wait on another.
7. Defect waste occurs when defective parts are produced. When repairable, these parts require subsequent operations.

[8] This material is based heavily on Professor David Cochran's unpublished class notes from *The Design and Control of Manufacturing Systems,* MIT:Spring 1998.

Upon this foundation Ohno sought to continuously identify and eliminate any and all sources of waste. Through a reduction of WIP, inventory, and other wastes, Toyota was able to become more responsive to customer demands in terms of volume and product variety at a lower cost—that is, balanced and synchronized[9] (see Figure 3-1). The goal of this project was to follow Ohno's example and design a more balanced and synchronized recycling system with minimal waste.

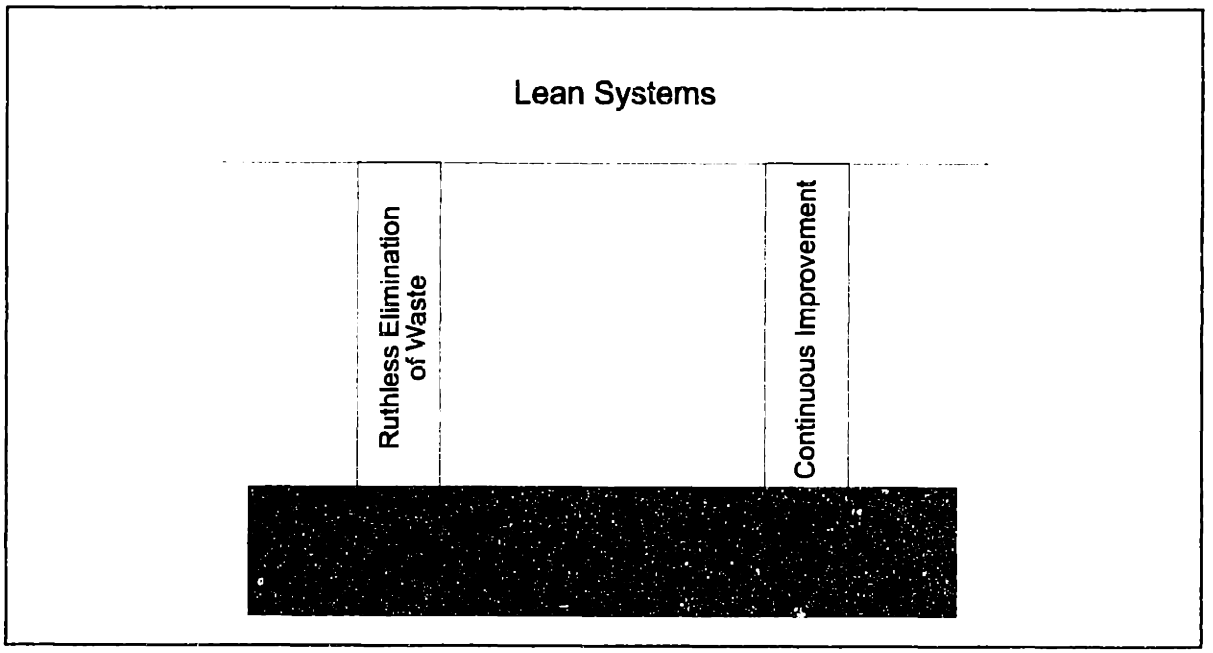

Figure 3-1[10]. The Lean Production Model. The pillars of lean systems, ruthless elimination of waste and continuous improvement, based upon a foundation of set-up time reduction, lead to a balanced and synchronized system.

In automobile recycling, there are no customers requesting crushed automobiles, the final product, randomly throughout the day as there are in new automobile sales. Moreover, crushed

[9] Balanced production is when all parts and final assemblies are produced at the same rate demanded by the customer. For example, if Toyota automobiles are sold at a rate of one per minute, then Toyota must produce engines, transmissions, door sets, ..., and final assemblies at a rate of one per minute. Boring engines at a rate of three per minute and only operating the boring machine for one third of the time that the assembly line operates is not considered balanced.

Synchronized production is to produce the mix of automobiles in the same order demanded by the customer. For example, producing all red automobiles on Monday, blue on Tuesday, etc. is only synchronized if customers only purchase red automobiles on Monday. If customers produce a mix of colors on any day, then to be synchronized, the same mix of automobiles must be produced each day in the order demanded by the customer.

automobiles are never ordered by make. For example, a call is never received for one crushed, full size, General Motors automobile. How then, can automobile recycling be balanced and synchronous?

As mentioned in Section 2, automobile arrivals at JMS facilities are random events. If we assume that the arrival (i.e. purchase) of any vehicle represents one customer order for a crushed vehicle of that type then we can strive for a balanced and synchronized recycling process.

In a balanced recycling system, the number of vehicles processed by each stage of the system each day would be equal to the average number purchased each day. For the system to be synchronized, vehicles would be processed in the same order that they arrive at the recycling facility. In this way, purchasing vehicle represents the introduction of raw material (i.e. one complete automobile) into the recycling queue to satisfy an imaginary customer order for a vehicle of exactly that type.

A caveat to the above discussion on a balanced and synchronized recycling system is that, because of the requirement for vehicles to be available for parts, the vehicles crushed each day are not the same vehicles that are purchased. That is, vehicles that are purchased will complete stage 1 of the recycling process and then be left in the parts-yard. Each vehicle introduced into the parts yard will signal the removal of a different vehicle from the parts-yard. In this manner, the system will remain balanced. To be synchronized, stage 1and stage 2 of the recycling process will also be consistent with respect to make. For example, for each General Motors vehicle placed into the parts-yard, a General Motors vehicle will be removed from the parts-yard and crushed.

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[10] This figure is based on course notes for *2.812 Design of Lean Manufacturing Systems*, Professor David Cochran, MIT, Spring 1998.

Section 4 Vehicle Recycling in Calgary

It is easiest to describe the recycling system used in Calgary by considering the process itself, the equipment used within the process, and finally the staffing policies. In this section, each of these aspects is described in detail here some performance data achieved with this system is presented. This section ends with a discussion of how this system compares to a lean system.

Process Description

The vehicle process flow is shown in Figure 4-1 on page 20. Vehicles are transferred from the scale directly to the *New Arrival Buffer* where they are stored until processed. The first stage of the process in Calgary is the *ground-activities* stage. For this stage, vehicles are transferred from the new arrival buffer to the drain shop with a forklift and placed on the ground in the location shown in Figure 4-2 on page 21. Ground-activities are:

- Siphon brake-fluid reservoir,
- Siphon power-steering fluid reservoir,
- Siphon windshield-washer fluid reservoir,
- Siphon engine coolant over-flow tank,
- Open trunk and prevent trunk from re-locking,
- Remove and discard jack, and
- Remove all trash from vehicle.

Elevated-activities follow the ground-activities and involve the following operations:

- Drain engine oil,
- Remove engine oil filter,
- Drain transmission oil,

- Drain differential oil (rear-wheel drive only),
- Drain engine coolant, and
- Cut fuel tank mounting-straps.

Because elevated activities-require access to the underside of the vehicles, a forklift truck is used to raise each vehicle approximately six feet and then rest the vehicles on the drain-rack (see figures 4-3a and 4-3b on page 22). To give the fluid adequate time to completely drain, the team performs the ground operations on a second vehicle at the adjacent drain-rack while the fluid drains from the first. Thus, two drain-racks are required in the drain shop.

From the drain-rack in the drain-shop, a forklift is used to transfer vehicles to the drain-rack at the fuel-drain station. At this station fuel tanks are drained of all fluids. Fuel is drained outdoors as fumes present a fire hazard when the drained indoors. Again, to allow adequate time for the fuel to drain from the fuel-tank, the staff performs other activities while the fuel drains (more on this later). When the fuel is drained, vehicles are transferred to the *Post-Drain* buffer

The post drain buffer is organized by vehicle type: General Motors products, Ford Products, Chrysler Products, and Imported products. Vehicles are removed from the buffer in a batch process based on a weekly schedule. For example, GM's are removed from the buffer Mondays, Chryslers are removed from the buffer Tuesday, etc. Wednesdays are reserved for making space in the parts-yard for the new vehicles, clean up, and equipment maintenance. Thus vehicles spend an average of 3.5 days in the post-drain buffer.

FUNCTION:	SYMBOL	TEAM
Weigh, inspect, and mark vehicle		Office
Scale to New Arrival area		Supplier
New Arrival buffer		
New Arrival area to Drain Shop		Drain
Ground station activities		Drain
Ground station to elevated station		Drain
Elevated station activities		Drain
Elevated station to Fuel-drain station		Drain
Drain Fuel		Drain
Fuel rack to post-drain storage area		Drain
Post-drain buffer		
Post-drain buffer to Parts-yard buffer		Set-Up
Parts-yard buffer		
Parts-yard buffer to parts-yard row		Set-Up
Pre-crush activities		Pre-Crusn
Transport to pre-crush buffer		Set-Up
Pre-crush buffer		
Radiator removal		Crush
Catalytic Convertor removal		Crush
Fuel tank removal		Crush
Crush		Crush

LEGEND

Process

Transport

Inspect

Vehicle Storage

NOTES:

**forklift to drain, loader to crush*

** stationary drain rack*

** radiators removed in crush yard*

** catylitic convertors removed in crush yard*

** fuel tanks removed in crush yard*

Figure 4-1. Process flow diagram of the recycling system currently used in the Calgary facility.

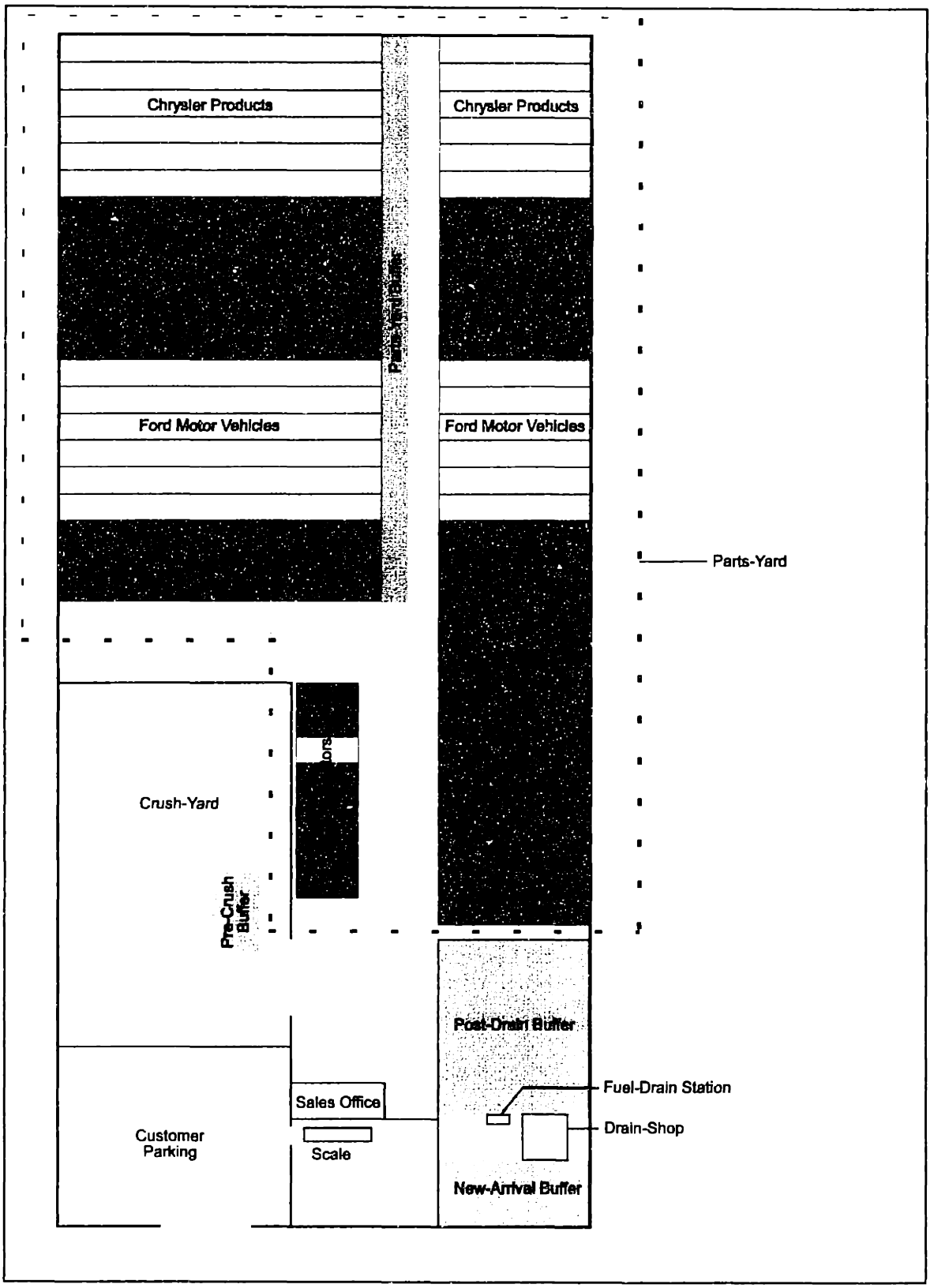

Figure 4-2. Site layout of the Calgary facility.[11]

[11] This drawing was recreated from a working drawing provided JMS management. The drawing provided by JMS was an original drawing based on site measurements.

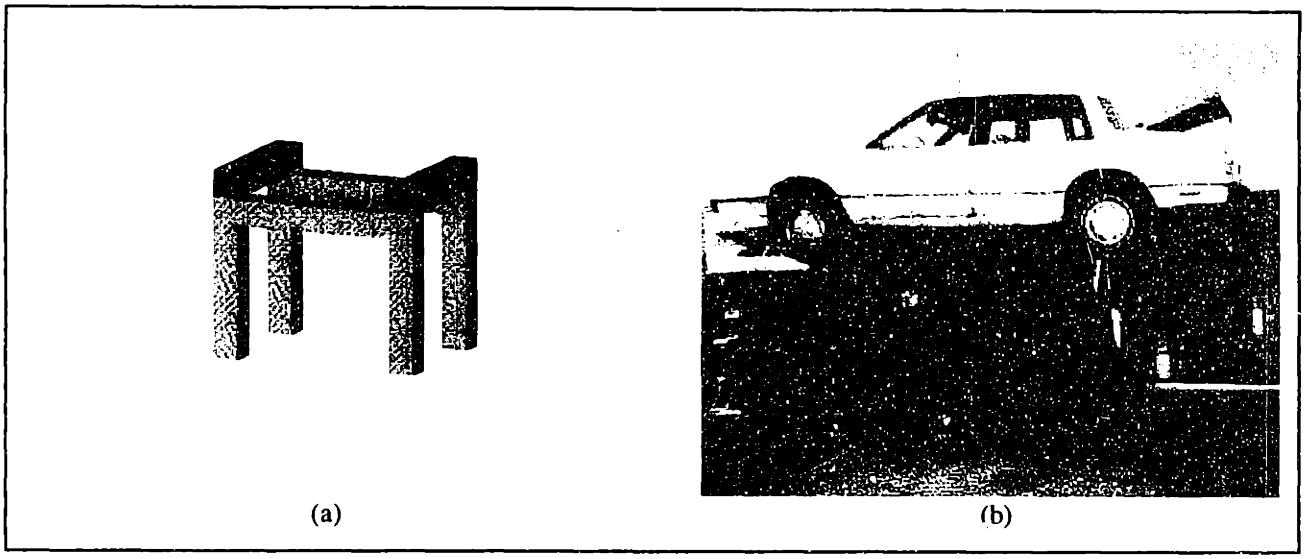

Figure 4-3. Stationary drain racks used for elevated actvities and draining fuel in the Calgary facility. A solid model of the rack is shown in Figure 4-3a[12] and a photograph of the rack in use is shown Figure 4-3b.

When removed from the post-drain buffer, vehicles are transferred to the parts-yard buffer in a batch process using a forklift. The number of vehicles required to fill a row of parts-vehicles usually determines the batch size. Vehicles are then transferred from the parts-yard buffer to the row and placed on stands. Those vehicles removed from the parts-yard are transferred to the *pre-crush* buffer.

A travel circuit is usually made by transporting one vehicle from the post-drain buffer to the parts-yard buffer, then removing one vehicle from the parts-row and transporting it to the pre-crush buffer, and finally returning to the post-drain buffer for another vehicle. This circuit is used to reduce the amount empty-travel by the forklift truck.

Prior to being removed from the parts row, phase 2 of the recycling begins for each vehicle. In this phase, all remaining starters, alternators, and compressors are removed from the vehicles as well as any loose parts with resale value. Also in this phase, radiator hoses are severed, wheels and tires are removed and any loose, non-saleable parts are placed inside of the vehicles.

[12] This is an original drawing.

Although outside of our design space, beyond the pre-crush buffer vehicles are prepared for crushing, crushed, and then sold. To prepare vehicles for crushing, any remaining radiators, catalytic converters, and fuel tanks are removed.

Staffing Policy

The process described above typically functions with 4 independent teams: 1) the *drain team*, 2) the *set-up team*, 3) the *pre-crush person*, and 4) the *crush team*. Each team is described herein.

The drain team is composed of two people and operates seven days per week (a total of 53 hours per person per week). Their responsibility begins at the new-arrival buffer and ends at the post drain buffer. The team performs all of the functions required to complete phase 1 of the recycling process (i.e. elevated activities, ground activities, and fuel drain).

The set-up team is responsible for all activities from the post-drain buffer up to, but not including, the pre-crush buffer. Thus, the team transports the vehicles from the post-drain buffer to the parts-yard, sets the vehicles on stands in the appropriate rows, and transports vehicles from the rows to the pre-crush buffer. However, prior to any vehicle leaving the parts-yard, the pre-crush person performs stage 2 of the recycling process (i.e. removes any remaining starters, alternators, compressors, etc.). The pre-crush person operates 40 hours per week over five days, however, approximately 8 of these 40 hours are spent on stage 2 of the recycling process.[13]

Again outside of our design space, from the pre-crush buffer the two-person crush team performs their responsibilities (i.e. removes any remaining radiators, fuel tanks, and catalytic converters; crushes the vehicles; and loads the vehicles onto trucks) in a 40-hour workweek.

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[13] The calculation of this estimate is provided in the *Pre-Crush Person Time Calculation* sub-section of Appendix B.

Equipment and Tools Used

During the first stage of the recycling process (i.e. the ground activities) fluids are recovered by using a vacuum line and small, portable tanks. Periodically, the tank contents must be transferred into large, stationary tanks. These tanks are the final destination for the recovered fluids. Trash and jacks are removed by hand and a hammer is used to damage the trunk-latch mechanisms. Like the fluids, the trash and jacks are stored in interim bins. The garbage bin is periodically emptied into a large, roll-away container. With the use of a forklift, the jack bin is periodically emptied into a vehicle that is to be crushed.

While on the drain-rack, the drain-team uses pneumatic punches to puncture engine oil pans, automatic transmission fluid pans, and differential covers. This provides a hole through which the fluids may escape. Manual transmission fluid is recovered by removing the threaded drain plug. Engine coolant is recovered by removing the radiator bleed-valve or by cutting the lower radiator hose with a knife—whichever is easiest. All of the fluids are gravity-fed into portable, 45-gallon drums—the contents of which are periodically pumped into 1500-gallon tanks. Similarly, fuel is drained into portable 45-gallon drums by using a pneumatic chisel to create a hole in the tank. The fuel is then pumped into a 1500-gallon tank using an electric pump. Oil filters are removed with a manual oil-filter wrench.

To transport the vehicles between drain-racks and buffers, the drain-team requires a dedicated, 8,000lb, dual-pneumatic, two-wheel drive forklift truck. Because the forklift operates inside of the drain-shop, it must generate relatively few harmful exhaust emissions. Thus, the forklift used by the drain-team in Calgary burns propane.

To shuttle and set-up vehicles, the set-up team relies entirely on a dedicated, 8000lb, rough terrain, four-wheel-drive, forklift. Unlike the drain-team, this forklift does not operate indoors and, therefore, is able to burn diesel fuel.

The pre-crush person does not transport vehicles and, therefore, does not require a forklift truck. This person relies almost entirely on mechanics' hand and pneumatic tools. With such tools as sockets, wrenches, ratchets, and a pneumatic socket-driver, the pre-crush person is able to remove all of the required parts. A ½-ton pick-up truck equipped with an engine-driven compressor is used to transport the suite of tools throughout the parts-yard.

Once again, the equipment used by the crush-team is outside of the scope of this project but, for completeness, it is described it here. To handle vehicles, the crush-team relies on a dedicated, 3 cubic-yard, articulating front-end-loader equipped with two 8-foot forks in place of the bucket. Prior to crushing any vehicle, the loader is used to remove all remaining fuel tanks, radiators, and any exhaust systems equipped with catalytic converters. A Mac-style crusher is used to crush vehicles. A hand-held, gas-powered, hydraulic shear is used to separate the catalytic converter from the exhaust system. Radiators, fuel tanks, and catalytic converters are then hand carried to the appropriate storage bin.

Productivity

The primary productivity measure used at JMS facilities is *the number of vehicles processed per day*. As a metric, this measure has both pros and cons. The pro is that the metric provides an aggregated mean daily throughput rate that includes activities not directly related to vehicle throughput (i.e. secondary activities). For example, activities such as transferring engine oil from the 45-gallon drum to the 1500-gallon tank will be included in this measure. However, the aggregation of these activities makes it difficult to identify troublesome aspects of the system.

Nonetheless, to facilitate communication with JMS personnel, the number of vehicles processed per day was also used as the primary metric here. Additional performance metrics include the area allocated to buffers, volume flexibility, and level of balance and synchronization. A data summary is provided in Table 4-1 below.

Metric:	Current Recycling System in Calgary
Drain-shop throughput	30 veh./day
System throughput (1 team)	20 veh./day
System throughput (2 teams)	30 veh./day
Land area allocated to buffers	lots
Total time in buffers	>3.5 days
System Flexibility	low
Balanced	No
Synchronized	No

Table 4-1. Productivity summary of current recycling system in Calgary.

For this thesis project, three methods of establishing system performance were used. The first was to calculate the performance from the acquired data. In terms of system performance, this meant videotaping, studying, and characterizing the entire recycling process in Calgary. Other measures required the use of existing engineering drawings as well as generating original measurements. The second method was to use JMS data recorded daily by JMS personnel. The final method, and in some ways the most reliable, was to interview the operations manager at the Calgary facility. The results of these efforts are described in the paragraphs that follow.

According to the operations manager, with two people on the drain-team, the drain-shop can process an average of 30 vehicles per day. This is limited to retrieving a vehicle from the new-arrival buffer, performing stage 1 of the recycling process, and then delivering the vehicle to

the post-drain buffer. To substantiate the operation manager's estimate, a daily average of 31.6 vehicles per day was calculated based on the annual production totals[14].

Based on videotape analysis, the drain-shop cycle time was found to be 34 vehicles per day[15]. The slight discrepancy is due to the secondary activities described above such as emptying bins. That is, the processing times established from the videotape were based on individual vehicles and did not include these secondary activities. From this, it is reasonable to estimate that approximately 10% of the drain-team's time is spent on secondary activities.

Using the method described in the *Process Description* sub-section above, the set-up team processes an average of 45-50 vehicles per day. It is interesting to note that, based on early findings of this project, the set-up team adjusted its modus operandi and was able to increase its throughput to 60 vehicles per day. Moreover, they were able to increase the size of the parts-yard through the elimination of the parts-yard buffer.

Based on the information provided thus far, it is clear that the drain-shop is the system bottleneck. Thus, the system throughput is restricted to 30 vehicles/day. However, because the system is divided into two segments with two independent teams, the system has no volume flexibility. That is, if both teams are operating then the system throughput is 30 vehicles per day. However, if one of the two teams is not operating then the system throughput is zero.

While parts of the system are balanced[16], the system as a whole is not. The average daily throughput of the drain-shop is balanced to the average daily purchase rate. However, the set-up team, with a throughput rate nearly twice the daily purchase rate is not balanced. As the activities of the pre-crush person and crush-team are dictated by the activities of the set-up team,

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[14] Management at the Calgary facility provided me with their corporate "scorecard" for the 1997 calendar year. To protect corporate secrets none of this data has been provided.
[15] Raw data is provided in Appendix A. Daily rates are based on a 7.5-hour work day.

these aspects of the system also not balanced to the daily purchase rate. It is impossible for an unbalanced system to be synchronized[17] and thus system used in the Calgary facility is neither balanced nor synchronized.

Discussion

With the exception of the drain-shop, the system is best described as a series of batch-and-queue processes. The goal has been to simulate mass production—many small steps performed repeatedly at high rates by "expert" staff. This system has several key deficiencies:

- Large variance in processing times makes balancing the system difficult,
- Buffers to compensate for this variance require a lot of space,
- Small subdivisions separated by buffers require excess handling of automobiles, and
- Randomness of arrivals requires that the schedule be deviated from regularly.

Vehicles arrive at the Calgary facility, like all other JMS facilities, in virtually any state of disrepair—some are complete and operable, some have been disassembled but are still complete, some have been disassembled and are incomplete, some have been in collisions, etc. Thus, the processing times of any stage within the system exhibit significant variability relative to the mean of the stage. As an example, the observed frequency distribution of the time to perform ground-activities is shown in Figure 4-4 on page 29. Superimposed on the frequency distribution is a Gaussian distribution with mean and standard deviation equal to that of the observed data.

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[16] Recall that a balanced recycling system was defined in Section 3 as one whose throughput equals the number of vehicles purchased on a per-day basis.

[17] Recall that a synchronized recycling system was defined in Section 3 as one which completely processes vehicles as they arrive regardless of the type.

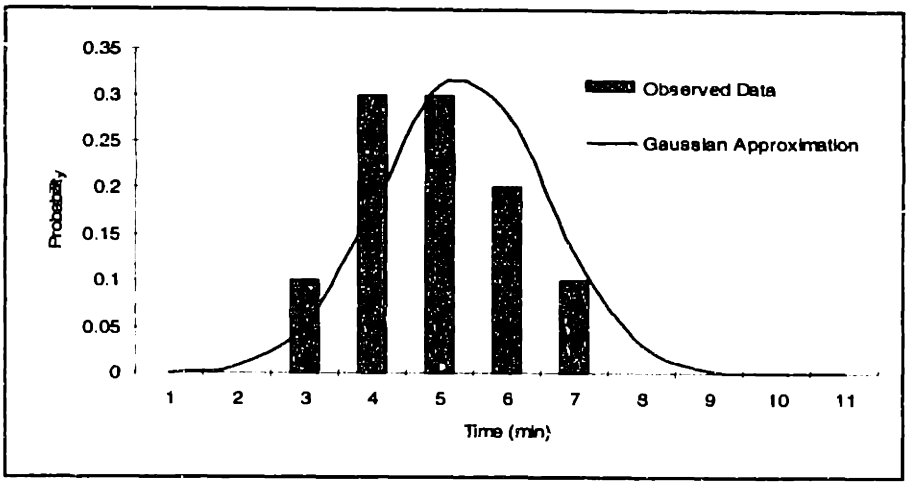

Figure 4-4. Probability Distribution of ground-activities processing time.[18]

In addition to the highly variable processing times, there is no identifiable correlation between processes. That is, a vehicle with a +2σ drain time may not have fuel and therefore require little time at the fuel-drain station (e.g. -2σ). The observed contributions to the total time in the drain-shop is shown for the ground-activities, elevated-activities, and fuel-drain is shown in Figure 4-5 below. Although not a robust statistical proof, it is reasonable to assume that no correlation between any of these exists.

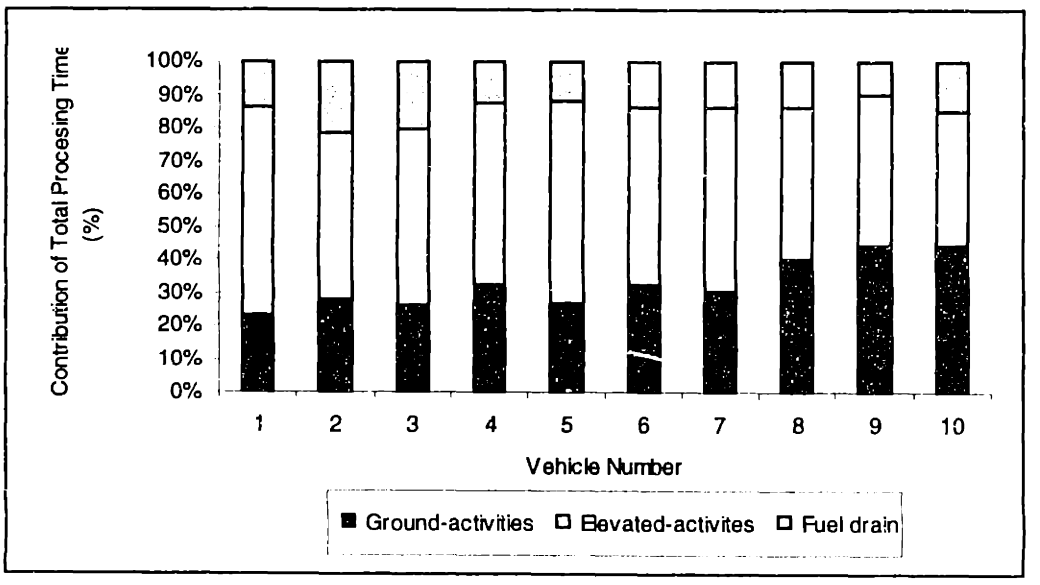

Figure 4-5. Observed relative contributions of the elevated-activities, ground-activities, and fuel-drain to the total time in the drain-shop.[19]

[18] This curve assumes the processing times are normally distributed. The mean and variance of the distribution were calculated from original data and are provided in Appendix A.
[19] Raw data is provided in Appendix A.

Thus, the system may not be balanced across all operations and/or processes. In an effort to prevent starvation of any operation due to the imbalance, large buffers have been placed between each of the operations (see Figure 4-1). While this solution leads to a system with minimal unproductive time within each of the operations, the buffers waste a tremendous amount of space. Indeed, in smaller facilities, more than 40% of the available land area may be allocated to non-value adding functions such as buffers.[20]

The use of buffers within the system also leads to significant handling and storage waste.[21] Storing in-process vehicles in buffers requires that, for each vehicle processed and each buffer, both the forklift and operator(s) must be diverted from their necessary trajectory two times: the first to deposit the vehicle in the buffer and the second to retrieve the vehicle. In addition to the wasted time, this also results in excess wear and tear on the forklift truck, as well as increasing the lead-time for each vehicle.

For this project, lead-time will be defined as the elapsed time between a vehicle arriving at the facility and its being crushed *less* the time spent in the parts-yard. Thus, given the current schedule, vehicles spend an average of 3.5 days[22] in the post-drain buffer (for Calgary, this represents an average buffer size of 100 vehicles). Thus, the average lead-time is 3.5 days *plus* the average processing time. However, because of the randomness of the arrival process described previously, the schedule must be regularly deviated from.

Currently, the randomness manifests itself as uncontrollable buffer levels at all stages of the process. As the set-up team processes one make of vehicles, the number of vehicles in the remaining post-drain buffers may undergo short periods of rapid growth. In an attempt to

[20] This data is based on the Denver facility. The data is net of allocations imposed by the county for such things as fire lanes and landscaping.

[21] Recall that Lean Production identifies the following seven wastes: Overproduction, Work in Process, Transportation, Processing, Motion, Waiting, and Defects.

address the problem, the set-up team must suspend the scheduled work to address the buffer congestion. Indeed, the Operations Manager at the Calgary facility once described managing the process as "putting out fires." Schedule deviations prevent forecasting and planning by any of the teams leading to a "seat of the pants" style of process management. Consequently, tremendous inefficiencies are introduced into the system.

In summary, no identifiable aspect of the system currently employed in the Calgary facility may be described as lean. The system operates in a mass-production, batch-and-queue mode; is not synchronized or balanced in any way; and possesses many sources of waste. It was anticipated that a well-designed system based on sound production principles would lead to higher productivity with fewer resources and be easier to manage. Thus, a lean system has been developed. As Peter Senge Says,

> *"When we fail to grasp the systemic source of problems, we are left to "push on" symptoms rather than eliminate the underlying causes."*[23]

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[22] For a proof and explanation of this estimate, please see the sub-section titled Lead-Time Estimate in Appendix B.
[23] Peter M. Senge, *The Leader's New Work: Building Learning Organizations,* The Slaon Management Review, Cambridge: MIT Press, 1990, p8.

Section 5 The Lean System Design

As in the previous section, the Lean System Design is described in terms of its elements. This section begins with a description of the proposed equipment, followed by a description of the process, and finally the staffing policy proposed to support the system. It is demonstrated how the lean recycling system is consistent with the Lean Production System Design Decomposition developed by Professor David Cochran of the Production System Design Lab at MIT. Based on empirical tests, a summary of the expected system performance is then provided as well as a discussion comparing the lean design to the system currently in use at the Calgary facility. It should be noted here that this is "first order" system design and possible areas of future development for the system are provided in Section 7.

Equipment Needed for the Lean System

Kansas City, Calgary, and St. Louis each use a different type of drain rack. Kansas City uses drain racks that hydraulically raise and lower vehicles allowing both ground and elevated activities to be performed without using the forklift to reposition the vehicle. However, the times to raise and lower vehicle are prohibitively long: 1 minute and 45 seconds respectively.

St. Louis, like Calgary, uses stationary racks.[24] However, the racks used in St. Louis are superior to those in Calgary in two ways. The first is that there is an elevated walkway along the front, rear, and driver's side of the vehicle allowing access to the hood, trunk, and interior respectively while the vehicle is elevated. This allows both elevated and ground activities to be performed in parallel. Second, drain-pans are attached to the rack to capture, and not mix, the fluids recovered from the vehicles eliminating the need for 45-gallon drums. Moreover, the

[24] For a description of the drain-racks used in the Calgary facility, see the Equipment sub-section in Section 4.

drain-pans drain directly into the 1500-gallon tanks thereby eliminating the need for secondary handling. The use of these racks for the lean system is proposed with three additional enhancements, two of which are results of employee interviews at the St. Louis facility.

The first enhancement is to extend the elevated walkway to the passenger side of the vehicle. This will provide access to all four sides of the vehicle allowing the vehicle interior to be accessed in the event that the driver's door is locked or damaged. The second enhancement is to add an additional drain-pan for capturing differential fluid. Currently, the same pan is used for both the transmission and differential fluids. Thus, the operator waits until the transmission has drained and then repositions the pan to drain the differential. An additional drain-pan would allow both the transmission and differential fluids to be drained in parallel. The proposed rack is shown in Figure 5-1 below.

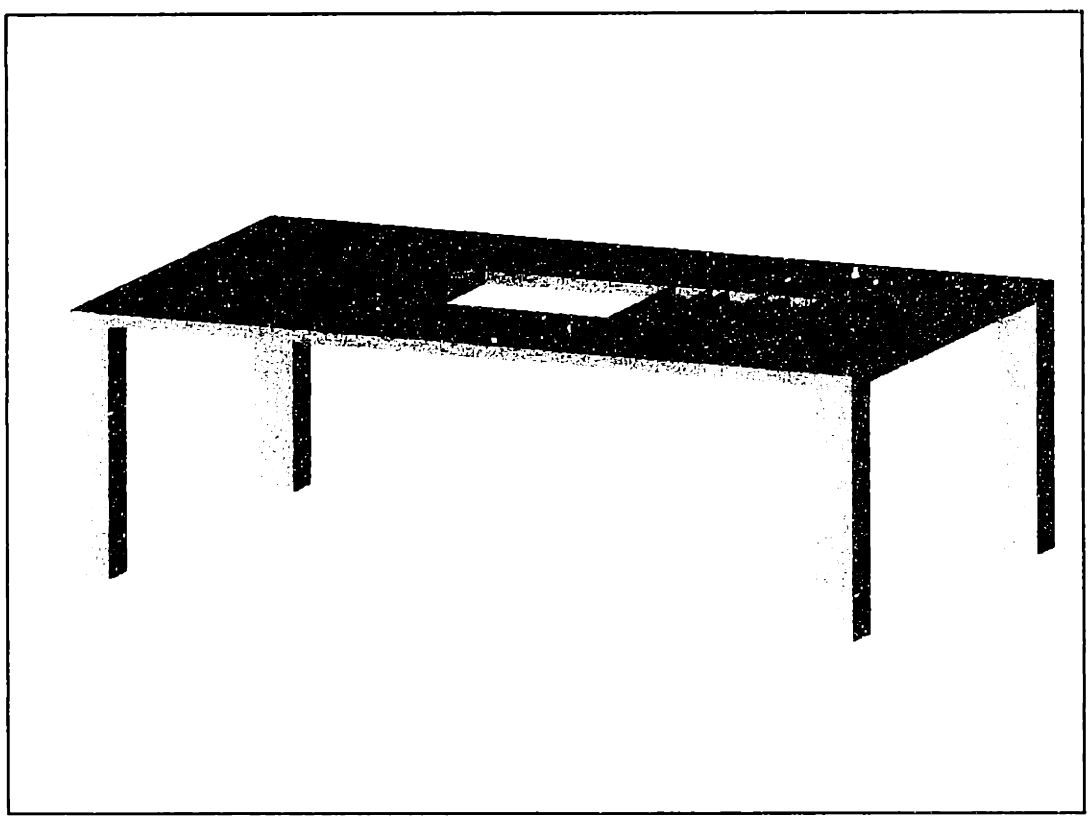

Figure 5-1. Drain-rack design for the Lean System.[25]

[25] The design of this drain-rack is based heavily on the drain-rack currently in use at the St. Louis facility.

The third enhancement is to modify the collection method of fluids. As mentioned in Section 4, in Calgary the oils and antifreeze are drained into 200-gallon, portable tanks or 1500-gallon, stationary tanks depending where the fluid is needed. That is, at times the fluids must be transported from the drain-shop to another location, which is accomplished through the use of the 200-gallon, portable tanks. To facilitate the tank filling process, a proposed tank and plumbing configuration is shown in Figure 5-2 below.

In this configuration, the fluids will fill a portable 200-gallon tank and not the 1500-gallon tank when a portable tank is present. When the portable tank is full, then fluids automatically begin to drain into the 1500-gallon tank. If no portable tank is present, then fluids automatically fill the 1500-gallon tank. Thus, a 200-gallon tank may be connected to the drain-rack and left to fill on its own. When full the fluid will then drain into the 1500-gallon tank. When the fluid is needed elsewhere, the staff need only disconnect the tank at the *quick-coupler*. Furthermore, a sight-glass is provided as a visual indication of when the 1500-gallon tank must be emptied.

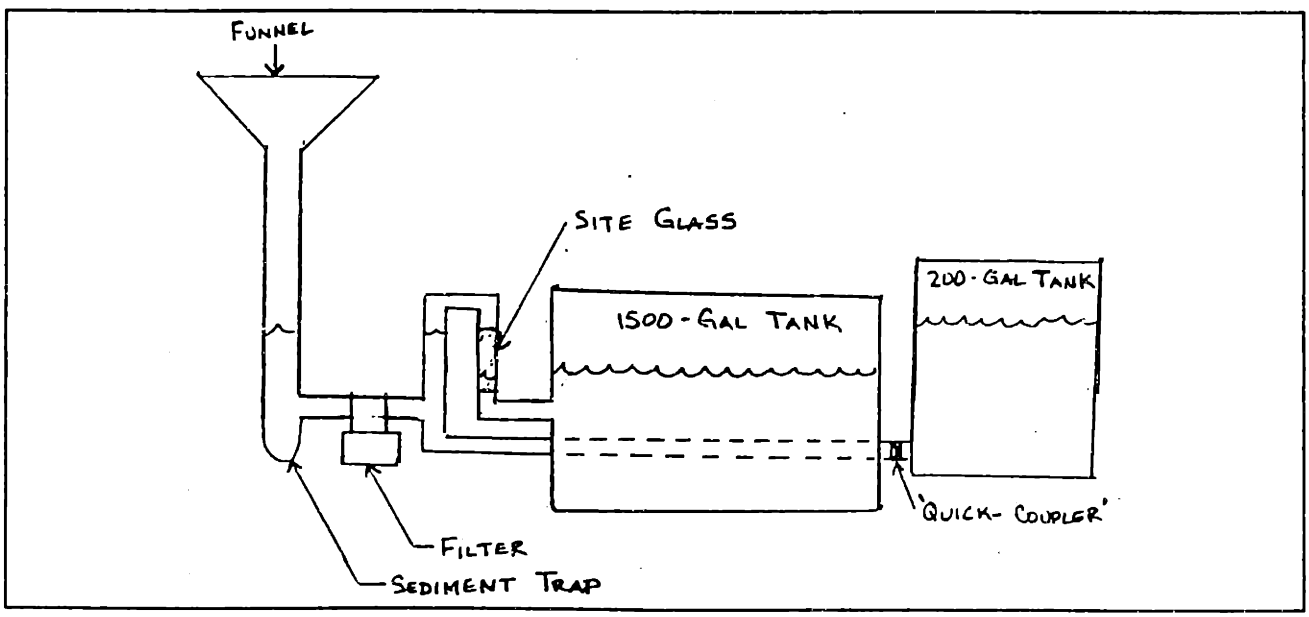

Figure 5-2. Proposed tank and plumbing configuration for the Drain-Rack.

The three primary benefits of the rack design for the lean system are 1) ground and elevated activities may be performed in parallel (because of the elevated walk-way); 2) vehicle repositioning (i.e. raising and lowering with or without a forklift) is not required; and 3) secondary handling of fluid is eliminated (because of the use of drain-pans and the tank and plumbing configuration).

To recover fuel, the use of a system similar to that in both St. Louis and Kansas City is proposed. Both St. Louis and Kansas City use the hydraulically powered punch and funnel system shown in Figure 5-3 below. This system is preferred over the pneumatic chisels used in Calgary as this system eliminates the need to remove the fuel tanks prior to crushing offering two benefits. The first, and most obvious, is that the number of process operations is reduced thereby reducing the mean system throughput time. The second is that the fastest known method of removing a fuel tank is to overturn the vehicle and "tear" the fuel tank out with a loader. In overturning vehicles, much of the debris (e.g. loose automobile parts and garbage) in the vehicle's interior fall onto the ground causing a considerable mess. Cleaning-up the debris necessitates secondary processing. Eliminating the need to overturn vehicles eliminates the need for secondary processing. As with the drain rack, one enhancement for the lean fuel-drain system is proposed.

(a) (b)

Figure 5-3. Proposed fuel drain station for the Lean System. Complete system shown in (a) and funnel and punch shown in (b).

At the fuel-drain station, the operator is required to put a minimum of four holes in the fuel tank with the punch. Currently, all positioning and control of the punch is performed manually. In the lean system, the initial positioning of the punch would be performed manually; however, the three subsequent repositioning and punching operations would be performed automatically. The automation of this step reduces the required manual time of this operation.

As will be described in the Process Description below, two forklifts will be required to operate both in the drain-shop and in the parts-yard. Thus, two 8000lb, rough terrain, four-wheel-drive forklift trucks will be needed. However, these machines will need to be operable indoors. Based on a discussion with Calgary's heavy equipment supplier, a filter may be added to diesel forklifts rendering them safe to operate indoors. Thus, acquiring equipment that satisfies the new requirements does not appear to pose any problems.

The remainder of the tools and equipment remain unchanged. A combination of air and pneumatic hand-tools are used for fluid recovery; a pick-up truck, compressor and hand-tools for stage two of the recycling process; and a 3 cubic-yard, articulating front-end-loader for crushing.

Process Description

The vehicle process flow for the Lean System is shown in Figure 5-4 on page 38. As before, vehicles arrive at the facility, are weighed, inspected, and transported to the new-arrival buffer. From the new arrival buffer, vehicles enter the drain-shop and are placed directly onto a drain-rack.

While on the drain-rack elevated activities are initiated but not completed. This provides the fluid sufficient time to drain. Initiating the elevated-activities includes:

- Drain engine oil,
- Drain transmission oil,

- Drain differential oil (rear-wheel drive only), and
- Drain engine coolant.

Following a delay to allow the fluids sufficient time to drain, elevated-activities are then completed in parallel with the ground-activities. Recall that, using the rack design described above, the ground-activities may be performed with the vehicle on the drain-rack. Ground-activities include:

- Siphon brake-fluid reservoir,
- Siphon power-steering fluid reservoir,
- Siphon windshield-washer fluid reservoir,
- Siphon engine coolant over-flow tank,
- Open trunk and prevent trunk from re-locking,
- Remove and discard jack, and
- Remove all trash from vehicle.

Completing the elevated-activities includes the following:

- Remove the engine oil filter,
- Remove the catalytic converter,
- Insert plugs into any holes created with the pneumatic punch, and
- Reinstall any drain plugs removed.

From the drain-shop, vehicles are transferred to the fuel drain-rack where the fuel is drained and, as described above, a minimum of four holes are created in the tanks. Immediately following the fuel-drain station, vehicles are transported to the parts-yard and placed directly on stands in the parts-row. Intermediate buffers are not used in the lean system.

As before, vehicles spend a fixed number of days in the parts-yard where they are available to retail customers for parts-sales. Just prior to being removed from the parts yard phase two of the recycling process begins.[26] To complete phase-two vehicles are transferred to the pre-crush buffer, prepared for crushing, and then crushed. As before, preparing vehicles for crushing requires that all remaining radiators be removed, however, catalytic converters and fuel tanks need not be removed in the lean system.

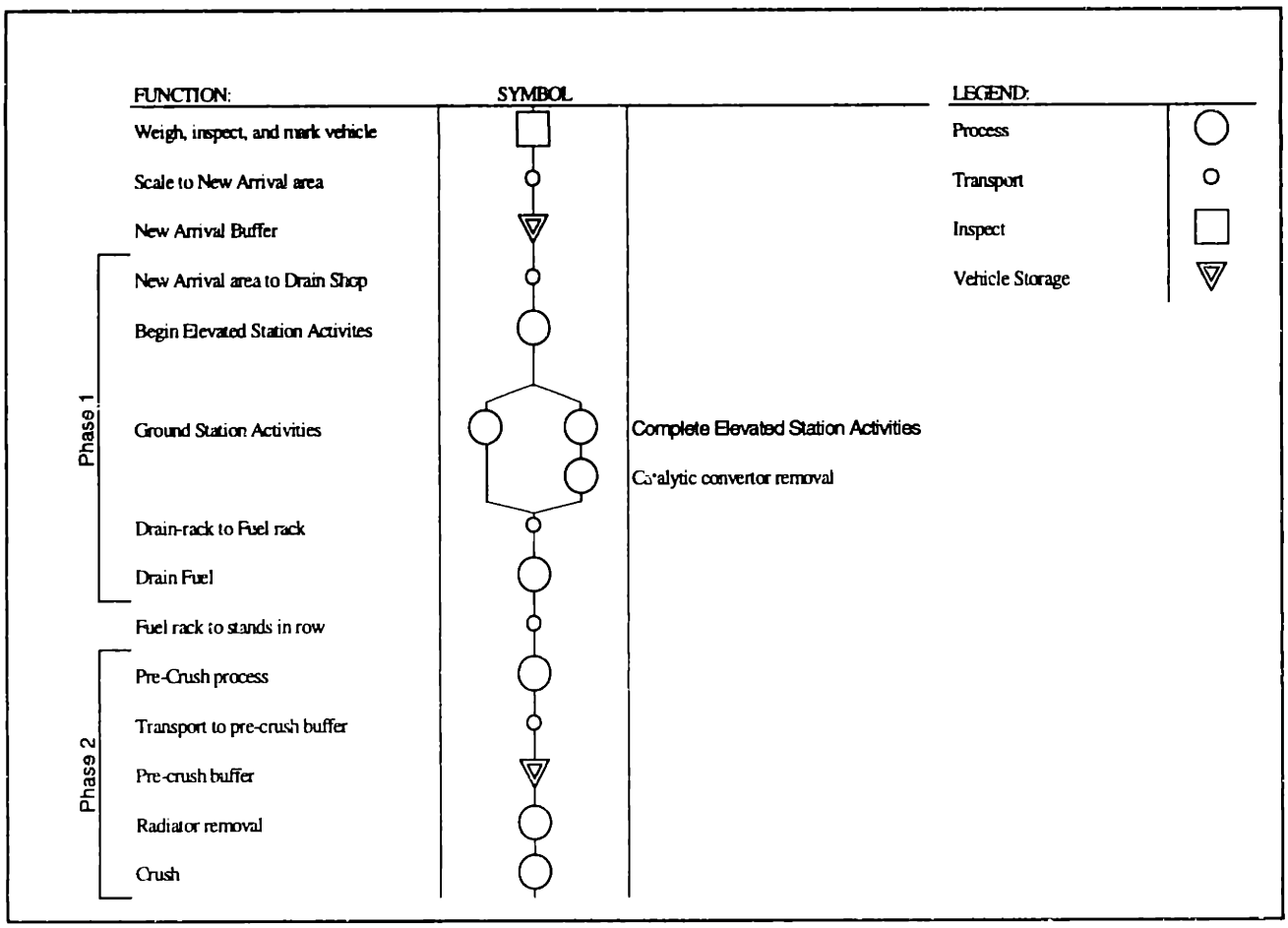

Figure 5-4. Lean system vehicle process flow.

[26] Recall that in this phase all remaining starters, alternators, and compressors are removed from the vehicles as well as any loose parts with resale value. Also in this phase, radiator hoses are severed, wheels and tires are removed and any loose, non-saleable parts are placed inside of the vehicles.

Staffing Policy

There are no intermediate buffers within the lean system. Thus, one team, which is again called the drain-team, is responsible for completely processing a vehicle in the drain-shop, transporting the vehicle to the parts-yard and setting in the parts-row, removing one vehicle from the parts-yard and delivering this vehicle to the pre-crush buffer. Effectively, the Lean system combines the duties of both the drain and set-up teams in the current system (the benefits of this policy will be described in the *Discussion* sub-section of this section). The motion-time chart for the drain-team is shown in Figure 5-5 below.

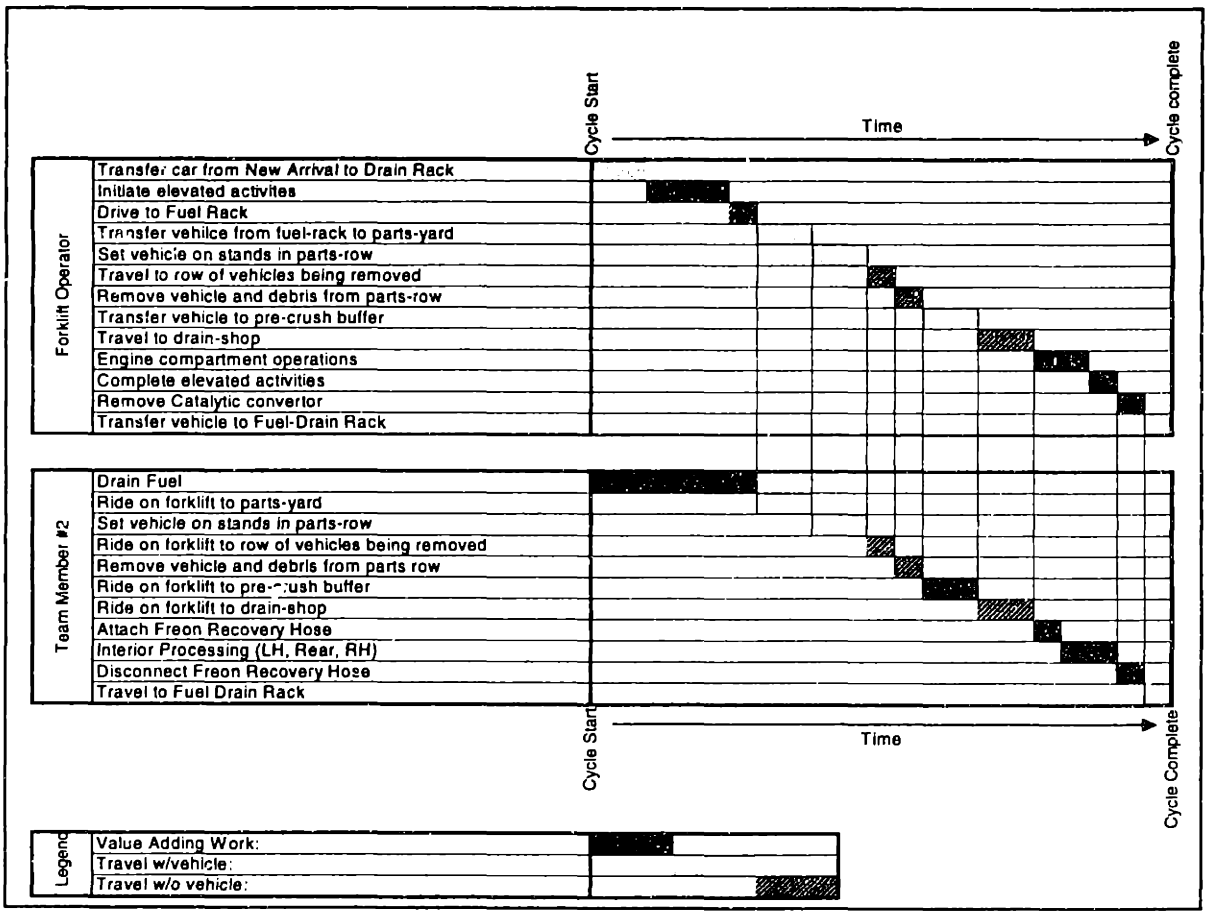

Figure 5-5. Drain-team motion-time chart for the Lean system.

Figure 5-5 shows that, with the exception of the beginning of the cycle, both team members process the same vehicle. The purpose of having the team process two different vehicles at the cycle beginning is to allow the fluids sufficient time to drain. Thus, as Team

Member #2 drains the fuel in one vehicle, the forklift driver places the next vehicle to be processed on the drain rack and initiates the elevated-activities.[27] Both team members then take the completed vehicle from the fuel drain-rack to the parts-yard while the vehicle on the drain-rack drains. This should provide sufficient time for the fluids in each vehicle to drain—even in the winter months.

It might also be noted from Figure 5-5 that with both team-members travelling together throughout the cycle, it becomes particularly important that efforts be made to reduce travel waste. As a first effort in achieving this a linear program was used in attempt to minimize the amount of travel by the drain-team.

The vehicles are sorted in the parts-yard by make. That is, each row shown in Figure 5-6 is assigned a vehicle type. The fraction of each type of vehicle in the parts-yard is roughly equal to the fraction of vehicles purchased. In this way, each vehicle spends the same amount of time in the parts yard. A goal was to select a new row-type assignment that minimized the forklift travel.

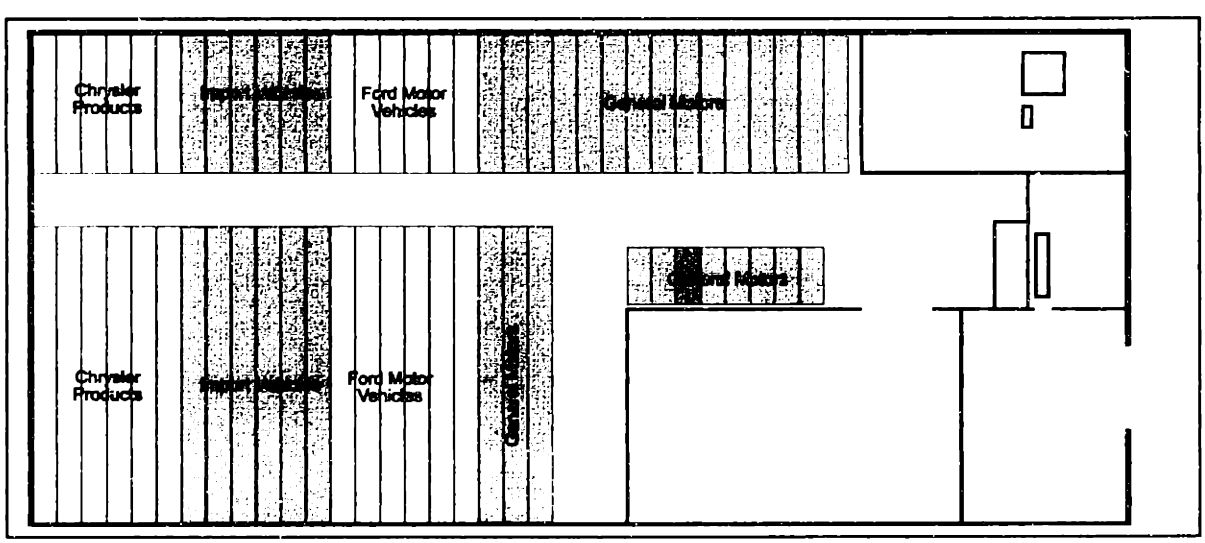

Figure 5-6. Current row assignments for the Calgary facility.

[27] Recall that initiating the elevating-activities includes draining engine oil, draining transmission oil, draining differential oil (rear-wheel drive only), and draining engine coolant.

The problem was modeled as a network assignment problem to take advantage of the efficient algorithms available for this type of problem.[28] Moreover, a network model with integral coefficients will provide an integral solution in terms of its decision variables. The network diagram is shown in Figure 5-7 below.

There are four initial nodes each representing one of the four types of vehicles—General Motors, Ford, Chrysler, and Import. The terminal nodes each represent one row in the parts yard. As shown in the figure, each row can be assigned any of the four types of vehicles. However, setting the sink at each terminal node equal to unity ensures that no more than one type of vehicle will be assigned to each row.

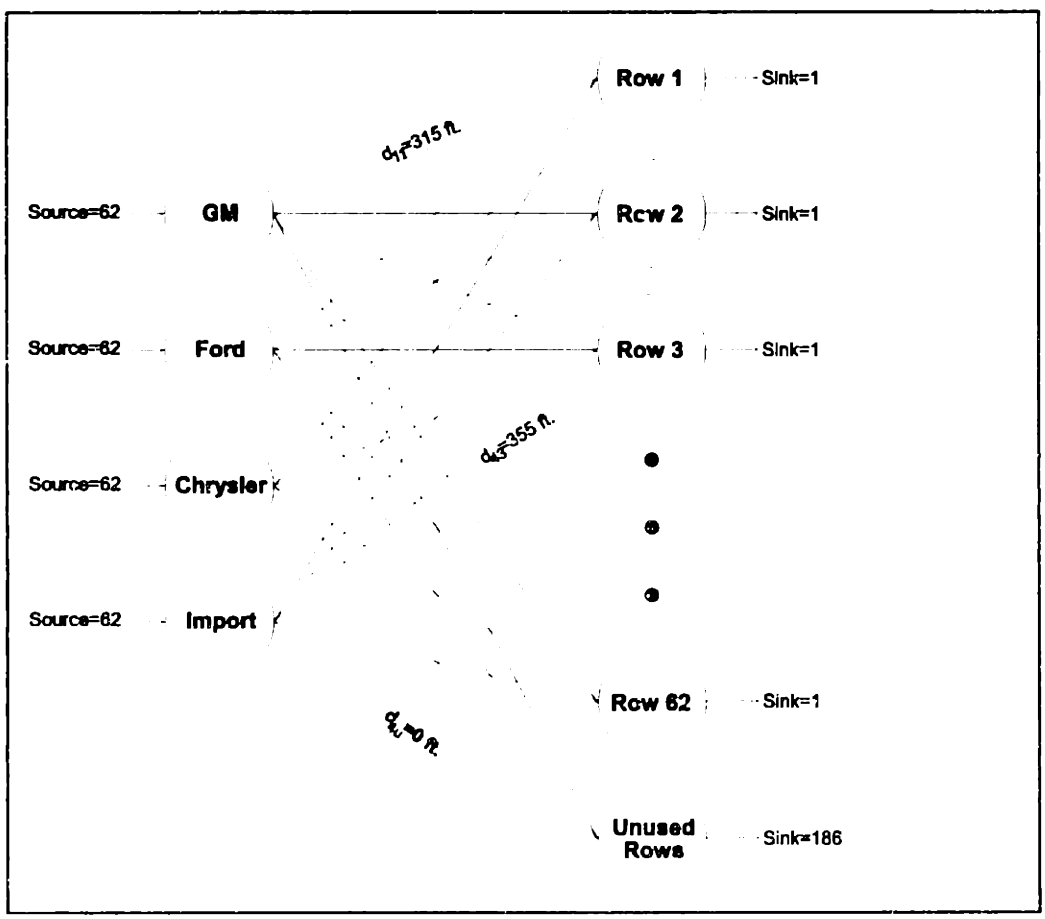

Figure 5-7. Network model used to assign vehicle types to rows.

[28] For a description of Network Flow Models see Wayne L. Winston, *Introduction to Mathematical Programming: Applications and Algorithms*, Belmont, CA: Duxbury Press, 1995, Section 8.

The decision variables are binary, 0-1, variables representing the assignment of a vehicle type to a row—1 if the type is assigned and 0 if it is not. In terms of the network, these represent the magnitude of the flow from node i to node j. Coefficients for each decision variable (i.e. the arc length) are the total distance traveled from the drain-shop to the center of the row represented by the destination node. The center of the row was used as this represents the mean distance traveled for all of the vehicles in the row.[29] Thus, the model objective function is as follows:

$$\text{Minimize:} \qquad D = \sum_{i=1}^{4} \sum_{j=1}^{62} x_{ij} * dj \qquad 5\text{-}1$$

Where D is the total distance traveled to each vehicle in the parts-yard one time, dj is the distance from the drain-shop to the center of the jth row, and x_{ij} is the flow from type-node i to row-node j (i.e. the decision variable).

Constraints are used to maintain flow balance through nodes and to ensure that there are sufficient rows of each type of vehicle in the parts-yard. At source and sink nodes, the flow balance constraints are as follows:

$$\textit{For each j:} \qquad -S_I = \sum_{i=1}^{4} x_{ij} \qquad \text{and} \qquad 5\text{-}2$$

$$\textit{For each i:} \qquad S_O = \sum_{j=1}^{62} x_{ij} \qquad 5\text{-}3$$

Where S_o is the magnitude of the source at the node and S_I is the magnitude of the sink. As the rows are different lengths, the number of rows assigned to each of the vehicle types was not known a priori. Thus, the source magnitudes were set to the total number of rows in the parts-yard. To account for the input/output imbalance (i.e. 248 source rows and 62 sink rows) a dummy node, named unused rows, was used. With a coefficient or travel distance of zero to the

[29] For an informal proof of this see the sub-section titled Centroid of Row in Appendix B.

dummy node, the optimization algorithm will only assign one vehicle type to each row and the remaining vehicle types to the dummy node. To prevent all of the source types from being assigned to the dummy node a *minimum demand* constraint was used.

The demand constraint imposes a minimum on the number of each of the vehicle types in the parts-yard. This also allows the fraction of each type of vehicle in the parts-yard to be controlled. As mentioned, the objective was to set the fraction of each vehicle type in the parts-yard equal to the fraction purchased giving every vehicle the same amount of time in the parts-yard. To achieve this, the following constraint was used:

$$\textit{For each i:} \qquad \frac{\sum_{j=1}^{62} x_{ij} n_j}{n} \geq f_i \qquad 5\text{-}3$$

$$\text{Or} \qquad \sum_{j=1}^{62} x_{ij} * n_j \geq f_i * n \qquad 5\text{-}4$$

Where n_j is the number of vehicles, or capacity, of the jth row, n is the total number of vehicles in the parts-yard, and fi is the ratio of type i vehicle purchased to the total number of vehicles purchased (i.e. the type fraction).

The model[30] was formulated in a spreadsheet using Microsoft Excel '98 and solved using the accompanying Solver.[31] The solution found is that row assignments have no affect on the total distance traveled by the forklift when the fraction of land area allocated to each type of vehicle is equal to the fraction of vehicles purchased. For example, data shows that 40% of the vehicles purchased are of type GM. Thus, if 40% of the land area is allocated to GM products then the location of the GM area does not matter. This result is easily understood.

[30] The model spreadsheet is shown in Appendix C: Minimum Travel Network.
[31] The model was solved using the Microsoft Excel '98 solver available as an Add-In with Microsoft Office '98. The spreadsheet formulation of the model is provided in Appendix C: Minimum Travel Network Model.

If the fraction of land area occupied is equal to the fraction of vehicles purchased for each type of vehicle, then for each N vehicles purchased where N is the number of vehicles in the parts-yard, every storage location in the parts-yard will be visited exactly once. Since every location will be visited exactly once and there are no tours (that is, vehicles are taken into the parts-yard one-at-a-time), the order in which the storage locations are visited does not matter. To help clarify this point, consider a paper route analogy.

If the delivery person could only carry one newspaper on her bicycle at a time, then she would have to load her basket with one newspaper, deliver the paper to one client, return to her home for another newspaper, and deliver this paper to her next client. Delivering papers in this way, the order in which she delivers the papers has no impact on the total distance traveled—she must travel to and from every client once each day. Of course, she could greatly affect her travel distance by carefully selecting a new home within her community based on the locations of her clients. How this alternative applies to the Calgary facility is left as a potential topic for future research and will be discussed further in *Section 7: Future Areas of Research and Analysis.*

As before, the pre-crush person begins phase-two of the recycling process in the parts-yard. However, because the drain-teams are processing vehicles in the order that they are received, batching by type will not take place. Thus, the drain-teams must communicate to the pre-crush person the number and type of vehicles processed. In this way, the pre-crush person may stay ahead of the drain-teams in terms of his or her duties. That is, for each vehicle taken into the parts yard by the drain-team, a vehicle of like type is ready to be removed. I expect that with a simple, manual communication system the pre-crush person will be able to stay ahead of the drain-teams by five vehicles or less.

In the current system, then drain-team operates seven days per week and the set-up team five days per week. However, based upon discussions with management at the Calgary facility, if the lean system is able to improve the throughput rate sufficiently, then the drain-teams may only operate 5 days per week.

The crush-team assumes responsibility for vehicles from the pre-crush buffer through loading trucks for delivery. As before, the team removes all remaining radiators, however, the team will not be required to remove catalytic converters and fuel tanks. Thus, throughput time for this process should be reduced considerably.

Comparison to Lean Production System Design Decomposition

Using the principles of Axiomatic Design, Professor Cochran has developed the Lean Production System Design Decomposition. The decomposition relates each functional requirement (FR) of a lean system to a design parameter (DP) which supports the FR. Essentially, the decomposition provides a "how" for each of the "objectives" that may arise while designing lean systems. In what follows, we use the relevant aspects of this decomposition to demonstrate how the proposed lean recycling design is consistent with the lean production methodology.

FR: Maximize Return on Investment. In the automobile recycling business, recyclable-material revenues are proportionally related to throughput while used-parts revenues are inversely related to the throughput. To satisfy the FR, throughput must be at its optimal value. For the purposes of this project, the current throughput rate was assumed to be optimal. Given the optimal throughput rate, the corresponding DP is to design a lean system—the purpose of this project.

FR: Produce at the Customer Demand Cycle Time. As mentioned, the current throughput rate was assumed to be optimal. Both systems achieve this throughput rate and are

thus consistent with the FR. However, the lean system offers more volume flexibility than the current system.

In the lean system each team follows a vehicle through the entire cycle in a single-piece-flow format. Although one cell cannot satisfy the arrival rate of vehicles, we estimate that two cells will exceed the mean arrival rate by approximately 50%. Thus, by varying the amount of time per day that the second cell operates the throughput can exactly meet the arrival rate at all times as required by the FR.

FR: Produce the Mix of Each Part Demanded per Time Interval. Like customer demand, the arrival of vehicles to be processed is truly random in terms of inter-arrival time and vehicle make. The arrival of a vehicle is, therefore, analogous to a customer order for one crushed vehicle of the type that has arrived. The system is designed to process all vehicles as they arrive without regard to make. Thus the system satisfies the FR.

FR: Eliminate Lot Delay. By eliminating buffers and completely processing each vehicle as it arrives, the lot size has been reduced to the theoretical minimum of one. Thus, lot delays have been eliminated. The FR has been satisfied.

FR: Ensure Predictable Time Output from Workers. In the new design, one team focuses on one vehicle from the arrival buffer through to the pre-crush buffer. Moreover, the tasks performed by each person have been standardized and balanced with respect to time. Thus, we anticipate that the time variance to process each vehicle will be minimized satisfying the FR.

FR: Respond Quickly to Production Problems. Because of the arrival randomness, the arrival buffer is required to prevent starvation of the recycling process due to very short-term fluctuations. However, in periods of elevated arrival rates or low processing rates due to equipment failures the buffer level may grow. Monitoring the new arrival buffer level will

provide immediate feedback regarding the state of the system and thus may be used to signal the need for the second team. Thus, the FR is satisfied.

FR: Reduce Transport Costs. Although the existing physical layout was assumed to be fixed, elimination of the buffers greatly reduced the amount of travel required. The savings are twofold: 1) the time spent in a non-value-adding activity has been reduced and 2) the wear-and-tear and the forklift is also reduced thereby satisfying the FR.

Productivity

Aspects of the Lean system were partially tested in Kansas City and St. Louis. A two-day, full-scale test took place at the Calgary facility and was video taped for further analysis. A description of the full-scale test and the results are presented below.

Because Calgary did not have the desired drain-racks for the test, we simulated the racks through the use of a forklift truck and an additional staff member. The forklift was used in place of the drain rack so that the vehicles may be raised and lowered allowing the drain-team to perform both the elevated and ground activities without repositioning the vehicle.

The team that performed the test was composed of one member from the drain-team and one member from the set-up team. This provided the team with some knowledge of the activities performed by the drain-team as well as some knowledge of the activities performed by the set-up team. To allow the team sufficient time to cross-train and become familiar with the new process, the test was run for two days. During this time the team members, necessary equipment, and any required support staff were dedicated to our efforts.

As before, the primary performance measure was the number of vehicles processed per day. On the first day of the test, the team processed 15 vehicles. On the second day, the team processed 18 vehicles. Moreover, on the second day the team lost 1.5 hours due to unexpected

circumstances. Despite these obstacles the team managed a 20% increase in productivity from the previous day. Based on these tests, the operations manager at the Calgary facility and myself both feel that a mean throughput rate of 25 vehicles per day is obtainable. This estimate, along with the remainder of the performance measures, is provided in Table 5-1 below.

Metric:	Current Recycling System in Calgary	Lean System
Drain-shop throughput	30 veh./day	N/A
System throughput (1 team)	20 veh./day	25 veh./day
System throughput (2 teams)	30 veh./day	50 veh./day
Land area allocated to buffers	lots	not much
Total time in buffers	>3.5 days	~1 day
System Flexibility	low	high
Balanced	No	Yes
Synchronized	No	Yes

Table 5-1. Productivity comparison of Calgary recycling system to the Lean system.

Given the estimate of 25 vehicles per day with one team, a throughput rate of up to 50 vehicles per day for two teams is anticipated. This represents four people—equivalent to the drain and set-up teams of the current system.

Comparing the 2-team system throughput of the two systems, it appears that the lean system increases throughput by 67%. This however, is misleading and thus requires some explanation. Peak throughput of the current system utilizes full drain-team capacity but approximately 50% of the set-up team's capacity (assuming, as discussed in section 4 that the set-up team can process approximately 60 vehicles per day). Thus, at 30 vehicles per day, the recycling system is at an *effective utilization* of 75%. Extrapolating the effective utilization to an 100% yields an *effective throughput* of 40 vehicles per day. Comparing this with the anticipated lean throughput of 50 vehicles per day, the lean system results in a 25% increase in *effective*

throughput.[32] The apparent 67% throughput increase is really a reflection of the volume-flexibility offered by the lean system.

In the lean system, throughput may vary between zero and 50 vehicles per day. However, although the current system has an effective throughput of 40 vehicles per day, the peak system throughput is 30 vehicles per day. Moreover, at 50 vehicles per day the lean system, unlike the current system, completely balanced and synchronized.

Without the post-drain and parts-yard buffers, the average time spent in buffers is reduced by more than 3.5 days. Although there is not sufficient data to do so currently, it will be possible to estimate the time spent by each vehicle in the new-arrival buffer. The buffer size that minimizes the land used without starvation may then be calculated. Until this calculation is complete, the current estimate of 1 day provided by the yard manager at the Calgary facility will be used.

Discussion

In Section 4 the key deficiencies of the current recycling system being used in Calgary were outlined. It is believed that the design presented above addresses all of these issues. Indeed, the lean system

- Is balanced,
- Uses half as many buffers,
- Eliminates nearly all of the unnecessary handling of vehicles, and
- Is not affected by the randomness of arrivals—synchronized.

Each of these issues are discussed in the paragraphs that follow.

[32] It is worth noting that the same result may be obtained by analyzing the one-team throughput of both systems

In the lean system, vehicles are queued for immediate processing upon arrival. Each vehicle is then processed right through to the parts-yard and a corresponding vehicle is taken from the parts-yard to the pre-crush buffer. Thus, all operations within the system are balanced to the arrival process. Compare this to the current system where the drain-shop may process one type of vehicle while the set-up team shuttles out a second type and deliver yet a third type to the pre-crush buffer. Moreover, the uniform processing pace of the lean system will provide a more steady flow of vehicles into the pre-crush buffer simplifying the management of this buffer level.

Because both members of the drain-team travel into the parts-yard and pre-crush buffer with the vehicles, it appears that there is considerable unproductive time for these people in the lean system. However, through the use of buffers, the current system possesses even more unproductive time but is able to mask this time by breaking it into small pieces spread throughout the process. For example, waiting during the set-up process by one member of the set-up team, excessive handling of vehicles, unnecessary travel into and out of the buffers, and indexing the three in-process vehicles through the drain-shop all contribute to the total unproductive time of the system.

The lean system uses half as many buffers. For the current system to be subdivided into many independent steps with more than one team (as it is), buffers must be placed between each of the steps. However, the relatively high processing-time variance combined with the unbalanced cycle times between the drain and set-up teams requires that large buffers be used to prevent starvation.[33] Eliminating the buffers allows the lean system to operate with considerably less land.

[33] Recall from Section 4 that the set-up team has a throughput 100% greater than that of the drain-team

This land may be allocated to more productive uses such as increasing the area allocated to parts-sales. Additionally, smaller land requirements will increase the number of prospective sites for future locations. Smaller sites will also reduce the start-up and operating costs for each new site.

Reducing the number of buffers has also had the indirect benefit of reducing the amount of travel by each vehicle. Storing in-process vehicles in buffers requires that each vehicle be diverted from its necessary trajectory into a buffer only to be removed later. Eliminating the buffer eliminates this travel waste.

In addition to reducing the travel, eliminating half of the buffers reduces the amount of handling required by each vehicle. Each time the forklift truck retrieves or deposits a vehicle, the driver must approach the target destination slowly to avoid collisions. When at the destination, the driver must stop the forklift, raise or lower the vehicle (depending on whether a vehicle is being retrieved or deposited), and finally, the forklift may resume its intended course. Thus, excess handling results in a major source of unproductive time for the operators. Moreover, damage often results as the forklifts have mild collisions with the vehicles. Reducing the damage incurred by the vehicles will undoubtedly lead to increased customer satisfaction.

Also contributing to improved customer satisfaction is the immediate processing and availability of parts vehicles. As mentioned, the current schedule is such that each type of vehicle is set-up once per week. Thus when a customer inquires about the availability of a particular vehicle stored in the new-arrival buffer or the post-drain buffer, he is informed that the vehicle will be available on the day of the week that type of vehicle is scheduled to be set-up. This presents two problems for the customer. The first is that the customer must return to facility

on or after the designated set-up day in anticipation of the vehicle being available—when feasible, an inconvenience at best.

Secondly, as mentioned, the "fire-fighting" nature of the operation leads to schedule deviations. Thus when a customer returns, he may find that the vehicle had been made available previously and thus the desired parts have been sold or he may find that the vehicle has yet to be set-up and thus must return for a third time. In the lean design, vehicles will be available for parts within hours of their arrival.

Section 6 Analytical Model of Optimal Throughput Quantity

Throughout this project one question remained unanswered: How many cars per day should any JMS facility process? To address this question, the optimal throughput quantity was analytically modeled[34]—that is, the throughput that maximizes corporate profit. The hypothesis is that there exists some finite, profit-maximizing throughput quantity.

To understand the hypothesis JMS revenue sources must be understood. JMS facilities have two major sources of revenue: the first is scrap material in the form of crushed vehicles and the second is the sale of used parts. It is presumed that scrap revenues are directly related to throughput rate while parts revenues are inversely related to the throughput rate.

The throughput rate determines the amount of time each vehicle spends in the parts-yard available for parts. Very low throughput rates allow vehicles to spend the most amount of time in the parts-yard but provide very low scrap revenues. Very high throughput rates, however, allow very little time in the parts-yard but very high scrap revenues. Indeed, in the limit of an infinite throughput rate vehicles would spend no time in the parts yard. Thus, some optimal quantity that takes advantage of both revenue streams may exist.

To begin, all revenues and all costs were expressed as a single equation—the profit equation. Profits on a per vehicle basis are

$$\pi_i = SP * W_i + PS_i + CS_i + OM_i - PP_i - VC_i - FC_i \qquad 6\text{-}1$$

where π_i is the profit from the ith vehicle processed. Scrap materials are sold on a per-ton basis and thus are captured as the product of the current scrap price, SP, and the scrap-weight of the ith vehicle, W_i. Additional revenues include parts-sales, PS_i, core sales, CS_i, and other materials,

[34] The technique used in this section is based on Section 8 of Robert S. Pindyck and Daniel L. Rubinfeld, *Microeconomics*, New York: Macmillan Publishing Company, 1989.

OM_i, such as copper and aluminum. Costs for the i_{th} vehicle include the purchase price of the vehicle, PP_i, variable costs, VC_i, in processing the ith vehicle, and the portion of fixed costs allocated to the ith vehicle, FC_i.

The total profit for the accounting period, Π, is the sum of the per-vehicle profits for all vehicles recycled during that period. Total profit is written as

$$\Pi = \sum_{i=1}^{N} \pi_i \qquad 6\text{-}2$$

where N is the number of vehicles processed over the accounting period. Similarly, total fixed costs may be represented as

$$FC = \sum_{i=1}^{N} FC_i \,. \qquad 6\text{-}3$$

Using similar reasoning, the total profit for the accounting period may be written as

$$\Pi = SP * \sum_{i=1}^{N} W_i^S + \sum_{i=1}^{N} PS_i + \sum_{i=1}^{N} CS_i + \sum_{i=1}^{N} OM_i - \sum_{i=1}^{N} PP_i - \sum_{i=1}^{N} VC_i - FC \,. \qquad 6\text{-}4$$

As mentioned in Section 2, JMS facilities receive their vehicles from two sources: 1) donation programs and 2) individual purchases. The price paid for vehicles received through donation programs is constant for all vehicles received. The price paid for all other vehicles is determined by each vehicle's weight. Thus the total paid for all vehicles may be written as

$$\sum_{i=1}^{N} PP = \sum_{j=1}^{L} PP_j^F + \sum_{k=1}^{M} PP_k^W \qquad 6\text{-}5$$

where L is the number of vehicles received through donation programs, PP_j^F is the fixed per-vehicle price paid for the jth vehicle, M is the total number of vehicles purchased on a per-ton basis, and PP_k^W is the purchase price of the kth vehicle purchased on a per-ton basis. Since donations and per-ton purchases are the only sources of vehicles for JMS,

$$N = L + M \ . \qquad 6\text{-}6$$

If it is assumed that the price-per-ton paid for any vehicle is constant over the accounting period, then the total paid for all vehicles recycled may be written as

$$\sum_{i=1}^{N} PP_i = \sum_{j=1}^{L} PP_j^F + PP^W \cdot \sum_{k=1}^{M} W_k^W \qquad 6\text{-}7$$

where PP^W is the price paid per ton and W_k^W is the weight of the kth vehicle.

The average weight of a scrap vehicle may be expressed as

$$\overline{W}^S = \frac{\sum_{i=1}^{N} W_i^S}{N} \qquad 6\text{-}9$$

where $\overline{W^S}$ is the mean weight of a scrap vehicle. Using a similar approach for the average purchase weight of vehicle being purchase on per-ton basis, parts-sales, core sales, and the sale of other materials and substituting into equations 6-7 and 6-9 into 6-4, the total profit may be written as

$$\Pi = N \cdot SP \cdot \overline{W}^S + N \cdot \overline{PS} + N \cdot \overline{CS} + N \cdot \overline{OM} - L \cdot \overline{PP}^F - M \cdot \overline{PP}^W \cdot \overline{W}^W - N \cdot \overline{VC} - FC \ . \qquad 6\text{-}10$$

Equation 6-10 assumes that both the purchase and scrap weights of vehicles are stable over time. History has shown this to be true for the purchase weight. In terms of scrap-weight, because JMS facilities sell most parts on an exchange basis, the average weight of scrap vehicles is expected to be reasonably stable over a large range of throughput rates.

The fifth and sixth terms of equation 6-10 represent the total cost of purchases for vehicles acquired through donation programs and per-ton purchases respectively. Assuming that, because of contractual arrangements with the charities administering the donation programs, the flat-rate purchase price, PP^F, is fixed and the number of vehicles received through these programs, L, is constant, then equation 6-6 may be substituted into equation 6-10 giving

$$\Pi = (L+M)\cdot SP\cdot \overline{W}^{S} + (L+M)\cdot \overline{PS} + (L+M)\cdot \overline{CS} + (L+M)\cdot \overline{OM} - L\cdot \overline{PP}^{F} - M\cdot \overline{PP}^{W}\cdot \overline{W}^{W} - (L+M)\overline{VC} - FC \qquad 6\text{-}11$$

To determine the profit maximizing equation in closed-form, total profit, that is equation 6-10, must be expressed solely as a function of the throughput. As discussed above, parts-sales per vehicle were assumed to be inversely related to throughput. However, it is also reasonable to assume those revenues from the sale of core parts and other materials are directly proportional to the throughput. That is, the average, per-vehicle revenue from core parts and other materials is constant for all vehicles regardless of throughput. If we also assume a positive elasticity of supply between the number of vehicles purchased on a per-ton basis, M, and the price paid per ton for those vehicles[35], then equation 6-11 is in a form differentiable with respect to a single variable—closed form.

Because the number of vehicles purchased on the per-ton basis, M, is the only variable contributor to the total throughput and all terms of the total profit equation, 6-11, are in terms of this variable, the derivative with respect to M is

$$\frac{d\Pi}{dM} = SP\cdot \overline{W}^{S} + (L+M)\cdot \frac{d\overline{PS}(L+M)}{dM} + \overline{PS}(L+M) + \overline{CS} + \overline{OM} - \overline{VC} \left[M\cdot \overline{W}^{W}\cdot \frac{d\overline{PP}^{W}(M)}{dM} + \overline{PP}^{W}(M)\cdot \overline{W}^{W} \right] \qquad 6\text{-}12$$

Revenues from scrap, core sales, and the sale of other materials (i.e. the first, fourth and fifth terms of equation 6-12 respectively) represent the fixed revenue per vehicle processed. That is, these terms are linearly-dependant upon M. Thus, let

$$\overline{FR} = SP\cdot \overline{W}^{S} + \overline{CS} + \overline{OM} - VC \qquad 6\text{-}13$$

[35] For a description of supply elasticity see Section 2 of Robert S. Pindyck and Daniel L. Rubinfeld, *Microeconomics*, New York: Macmillan Publishing Company, 1989.

where $\overline{FR}$ is the average fixed revenue per vehicle less the variable costs. Substituting 6-13 into 6-12 and letting

$$\frac{d\Pi}{dN} = 0 \qquad 6\text{-}14$$

to find the maximum gives

$$0 = \overline{FR} + (L+M)\cdot\frac{d\overline{PS}(L+M)}{dM} + \overline{PS}(L+M) - M\cdot\overline{W}^{W}\cdot\frac{d\overline{PP}^{W}(M)}{dM} - \overline{W}^{W}\overline{PP}^{W}(M) \qquad 6\text{-}15$$

The relationship between per-vehicle parts-sales and throughput is currently unknown. However, to proceed it was assumed that the cumulative parts-sales for any vehicle is related to time by the exponential and may be written as

$$PS(t) = PS(1 - e^{\lambda t}) \qquad 6\text{-}16$$

where PS is the peak-parts-sales scaling factor and λ is the inverse of the cumulative parts sales time constant.

Equation 6-16 implies that the cumulative parts-sales per vehicle asymptotically approaches some limit, PS, as shown in Figure 6-1 on the following page. Said in an alternative way, the rate of parts-sales for any vehicle decreases with time to a limit of zero.

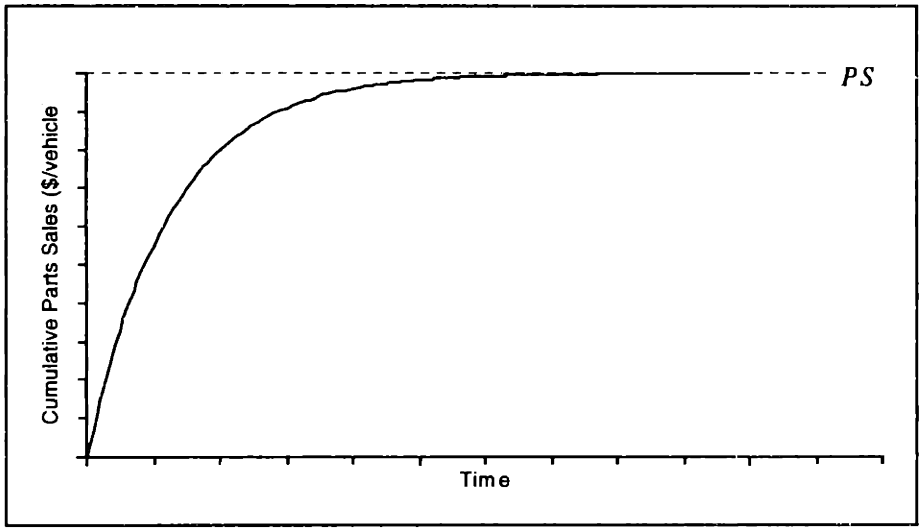

Figure 6-1. Relationship between time and cumulative parts-sales per vehicle.

For the purposes of the model, cumulative parts-sales must be related to throughput. Because the number of vehicles in the parts-yard (i.e. capacity) is always constant, the time spent by any vehicle in the parts-yard is the ratio of the parts-yard's capacity to the throughput. That is,

$$t = \frac{C}{L+M} \qquad 6\text{-}17$$

where t is the time in the parts-yard and C is the capacity of the parts-yard. Substituting equation 6-17 into 6-16 gives the following relationship

$$PS(L+M) = PS(1 - e^{-\lambda \frac{C}{L+M}}). \qquad 6\text{-}18$$

As the throughput *(L+M)* in equation 6-18 approaches zero, parts-sales per vehicle *(PS(L+M))* approaches the ceiling of parts-sales *(PS)*. Similarly, as the throughput *(L+M)* approaches infinity, parts-sales per vehicle *(PS(L+M))* approaches zero. Thus, equation 6-18 is consistent with our previous assumptions.

The derivative of equation 6-18 may be written as

$$\frac{dPS}{dM} = -\frac{PS \cdot \lambda \cdot C}{(L+M)^2} e^{-\lambda \frac{C}{L+M}}. \qquad 6\text{-}19$$

Subbing equations 6-18 and 6-19 into 6-15 and rearranging gives the following

$$0 = \overline{FR} - \frac{PS \cdot \lambda \cdot C}{L+M} e^{-\lambda \frac{C}{L+M}} + PS(1 - e^{-\lambda \frac{C}{L+M}}) - M \cdot \overline{W}^{W} \frac{d\overline{PP}^{W}(M)}{dM} - \overline{W}^{W} \cdot \overline{PP}^{W}(M). \quad 6\text{-}20$$

The constant terms, $\overline{FR}$ and PS, in equation 6-20 represent the total available revenue from any vehicle less the variable costs: scrap sales, core sales, the sale of other materials, and the peak parts-sales. Therefore, let

$$TR = FR + PS \quad 6\text{-}21$$

where TR is the total available revenue from any vehicle. Substituting equation 6-21 into 6-20 and rearranging gives the following equation for maximum profit:

$$0 = \overline{TR} - PS \cdot e^{-\lambda \frac{C}{L+M}} \left(\frac{\lambda C}{L+M} + 1 \right) - M \cdot \overline{W}^{W} \frac{d\overline{PP}^{W}(M)}{dM} - \overline{W}^{W} \cdot \overline{PP}^{W}(M). \quad 6\text{-}22$$

Based on the assumptions described above, equation 6-22 represents the profit maximizing equation in terms of the throughput rate.

Consider the four terms of equation 6-22. The first term represents the total available revenue from a vehicle. That is, the revenue that would be recognized if the vehicle were spend sufficient time in the parts yard to achieve the peak parts sales and then crushed and sold.

The second term represents the effect that throughput has on parts-sales. As throughput increases, the magnitude of the second term also increases thereby subtracting more from the total available revenue. For an infinitely large throughput the magnitude is PS which reduces the total revenue to simply scrap, core, and other materials revenues. Additionally, because L is assumed to be constant, there is a minimum, non-zero throughput rate.

The third and fourth terms are the effects that that the purchase-price has on profitability. More specifically, the fourth term simply reduces total revenue, TR, by the cost of purchasing M vehicles. The third term is the effect that the supply elasticity has on vehicles. For a positive

supply-elasticity, the purchase-price must be increased to increase the throughput (i.e. M). The third term thus reduces the total revenues by the additional paid for every vehicle. A similar argument holds for reducing the purchase-price. In what follows the optimal throughput quantity for a specific supply-elasticity case is considered.

Supply Elasticity Equal to Zero

A supply-elasticity equal to zero implies that the price paid per ton for vehicles has no effect on the number of vehicles that JMS acquires. That is, JMS may obtain as many or few vehicles as it likes at the market-clearing price. Mathematically, this implies that $\frac{dPP}{dM} = 0$. In terms of economics, this may be represented by a horizontal supply curve as shown in Figure 6-2 below.[36]

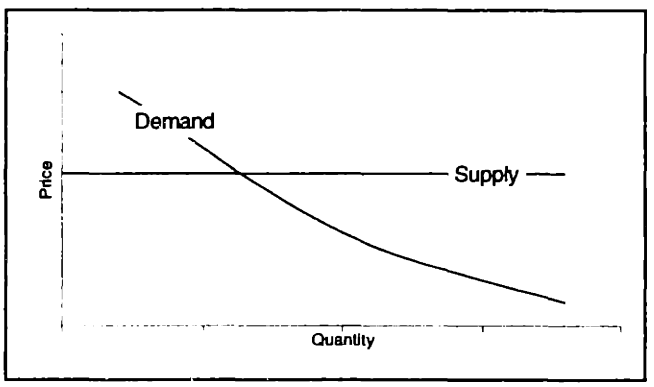

Figure 6-2. Vertical, linear supply curve.

Making this substitution into equation 6-22 yields the following:

$$0 = \overline{TR} - PS \cdot e^{-\lambda \frac{C}{L+M}} \left(\frac{\lambda C}{L+M} + 1 \right) - \overline{W}^{W} \cdot \overline{PP}^{W} . \qquad 6\text{-}23$$

Using equations 6-13 and 6-21, equation 6-24 may be written as

[36] Robert S. Pindyck and Daniel L. Rubinfeld, *Microeconomics*, New York: Macmillan Publishing Company, 1989, P38.

$$0 = \left(SP \cdot \overline{W}^{S} + \overline{CS} + \overline{OM} - VD - PP^{W} \cdot \overline{W}^{W}\right) + PS - PS \cdot e^{-\lambda \frac{C}{L+M}} \left(\frac{\lambda C}{L+M} + 1\right) \qquad 6\text{-}24$$

where the first term represents the *net profit* from a vehicle excluding parts-sales, the second term represents the peak available revenues from parts-sales, and the third term represents the effect, or penalty, on parts-sales for turning-over the inventory in the parts-yard. Dividing equation 6-25 through by *PS* gives

$$0 = \frac{SP \cdot \overline{W}^{S} + \overline{CS} + \overline{OM} - VC - PP^{W} \cdot \overline{W}^{W}}{PS} + 1 - e^{-\lambda \frac{C}{L+M}} \left(\frac{\lambda C}{L+M} + 1\right) \qquad 6\text{-}25$$

where the first term may be referred to as the *normalized net profit*, the second term the *normalized peak parts-sales* and the third the *normalized effect of turnover*. The optimal throughput given by equation 6-25 is that value of *M* for which the result is zero. However, *M* may not be isolated from this equation and thus to gain an intuitive understanding consider the terms of the equation.

The first term, the normalized net profit, represents the ratio of available pre-parts-sales profit from a vehicle to the maximum available revenues from parts-sales. If this term is greater than unity then the profit excluding parts-sales is *greater* than the available parts sales. Values between zero and unity, imply that there is some profit to be made without parts-sales, however, the maximum contribution from parts-sales will be greater. Finally, values less than zero, imply that only losses are possible without parts-sales.

For a unique and defined optimal throughput to exist, the right-hand side of equation 6-25 must be zero. As shown in Figure 6-3 on the following page, the normalized effect of throughput, the effect of throughput begins at zero and asymptotically approaches unity.

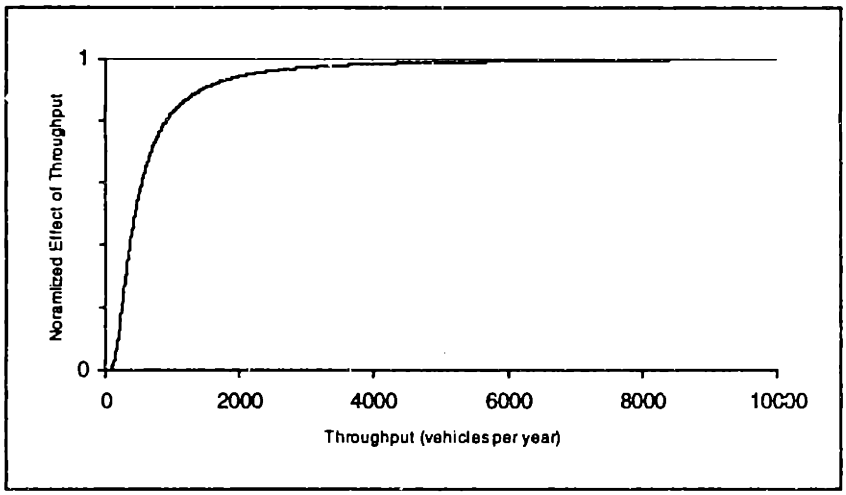

Figure 6-3. Normalized effect of throughput versus throughput

Because the curve shown in Figure 6-3 is subtracted from the first two terms of equation 6-25, it is clear that, for the right-hand side of equation 6-25 to be zero, the sum of the first two terms must be between zero and unity.

The first two terms of equation 6-25 may be thought of as *one* (i.e. the second term) plus some number (i.e. the first term). For the sum of these two terms to be between zero and one, the first term must be between zero and *negative one*. As mentioned previously, this represents the case where parts-sales are required to be profitable. Thus, for the optimal throughput to be unique, the net profit excluding parts sales must be negative *but* less than the maximum available revenue from parts-sales. This case, along with the two other possibilities, is shown in Figure 6-4 on the following page.

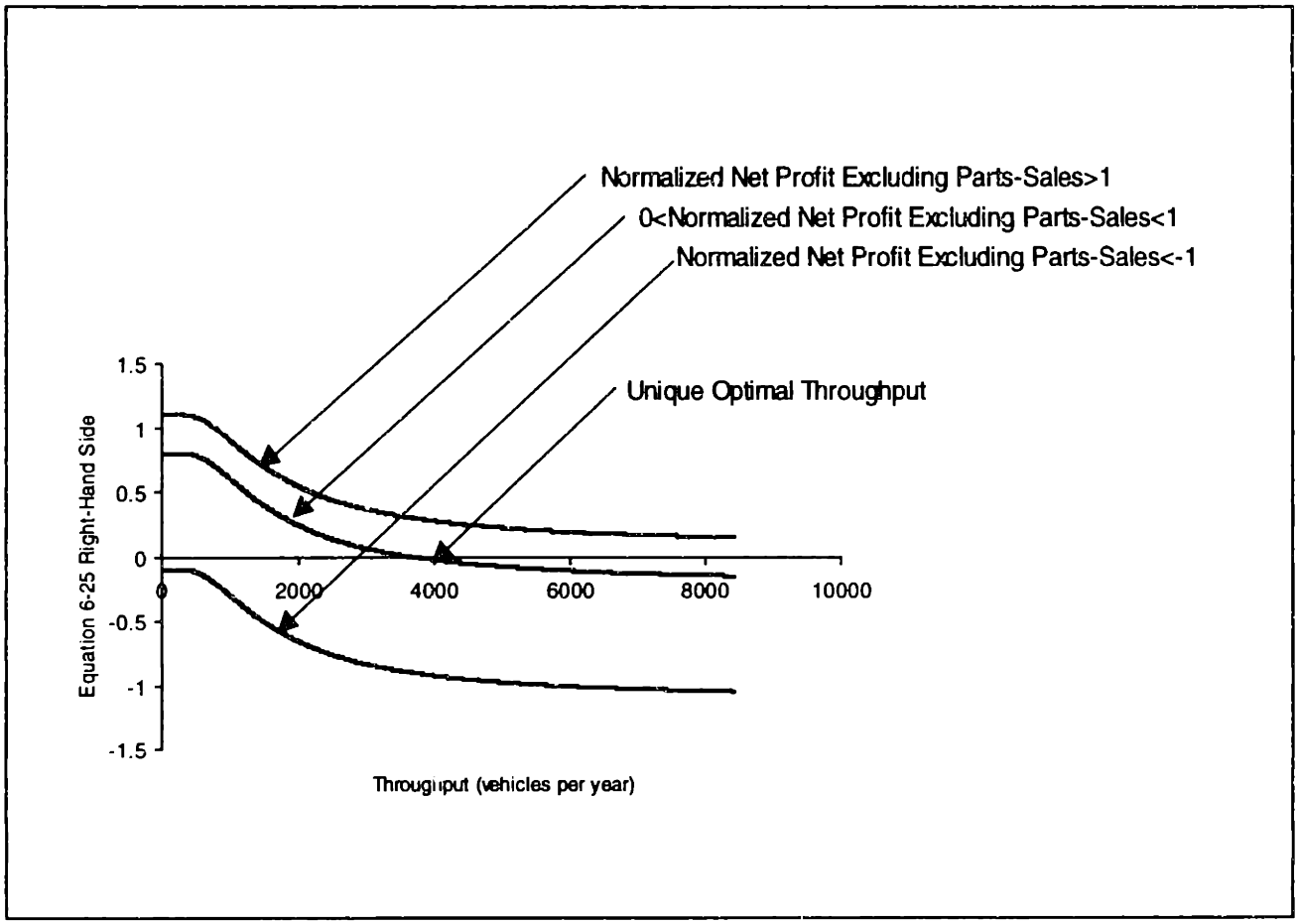

Figure 6-4. Plot of the right-hand side of equation 6-25 for three values of Net Profit Excluding Parts-Sales.

In Summary, three conclusions may be drawn from the analysis presented in this section:

4. if there is a profit to be made per vehicle excluding parts-sales then the profit maximizing throughput quantity is infinity,

5. if the net loss per vehicle excluding parts sales is less than the maximum potential revenue from parts-sales then a unique optimal throughput exists and should be sought, and finally,

6. if the net loss per vehicle excluding parts-sales is greater than the maximum potential revenues from parts-sales then no throughput will produce profits and a new career path should be considered.

Section 7 Areas of Future Research

There is still a significant amount of research to be performed. Two key areas are:

1. Improvements to the Lean System Design presented in section 5 and
2. Refinements and parameterization of the Analytical Model of Optimal Throughput Quantity presented in section 6.

An outline the work to be done in each of these areas follows.

Lean Recycling System Improvements

The research and design efforts presented in this thesis reflect an initial, first-order attempt to improve the process used at JMS facilities with respect to very specific objectives. The system design is now at a stage suitable for implementation. After the effects of introduction transients and learning curves have passed, two research and design efforts are needed. The first is to expand the scope of the current research in two major areas.

As mentioned in *Section 2: Project Design Space,* the system boundaries for this project were established at the new-arrival buffer and the pre-crush buffer. The scope of the lean efforts should be extended to also include these areas. For example, the purchase process and information flow of newly purchase vehicles may be studied to identify and eliminate sources of waste. Another example of scope expansion would be to incorporate the crush process into the recycling system. I expect significant benefits in this area as the crushing equipment is automatic and remotely controlled. Thus, it is conceivable that the drain-team may remove a vehicle from the parts-yard, place the vehicle directly in the crusher, begin the crush-cycle, and return to the drain-shop.

A second area of major scope expansion is to consider site layout prior to development. As described in *Section 5: Lean System Design*, when the site layout is fixed, no improvements are possible with respect to total travel distances and times. However, if careful consideration is given to site layout prior to development, significant travel-time savings for the drain-team may be recognized. For example, co-locating the new-arrival buffer and crusher-yard may save a significant amount of travel. For this effort, a network model similar to that used in this thesis will be a useful tool. Consideration should also be given to those areas not directly affected by the recycling system such as the sales area and customer flows throughout the facility.

The second research and design area is a second-order, or more detailed, study of the lean recycling process. These studies should seek to further identify and eliminate wastes through a careful focus on the process steps. For example, such studies may seek to improve the balance of the process steps within the system, increase the level of standardization, and perhaps include the design of new tools for specific tasks

It is expected that through careful study and analysis and ruthless implementation, Lean Production methodologies may be extended throughout the entire organization.

Refinement of Analytical Model

While the analytical model presented in *Section 6: Analytical Model of Optimal Throughput Quantity* provided some intuitive insights and for small perturbations about the current state, the model may be both refined and parameter estimates established.

The most significant refinement will model expansion to include the supply curve effects. That is, the current model assumes that all vehicles have the same purchase price regardless of volume. Supply-curve effects will correlate the average purchase-price of a vehicle to the

system throughput. Different effects may be considered such as linear and parabolic supply curves.

For the model to be truly useful in practice and beyond just an intuitive understanding, reliable parameter values are required. It is expected that carefully controlled empirical studies will provide the information desired. Estimation of model parameters is important for two reasons.

The first is that, given reliable parameter values, the model may be used to establish and monitor throughput values and their effect on profitability. For example, informed decisions may be made regarding such dynamic events as short-term supply fluctuations, fluctuations in the scrap metal prices, and the amount of effort that should be expended recapturing core-parts.

The second powerful use for reliable parameters is performance projections of future sights. If it is possible to relate internal parameters to external factors then the performance of new facilities may be accurately predicted. For example, if the purchase-rate parameter, λ, can be related to such external factors as regional population size and average income, then the purchase-rate for new sites may be calculated. With all of the parameters, the optimal throughput rate and potential profitability for any future sight may be estimated. This would be a very valuable tool for JMS executives.

Section 8 Conclusion

In this thesis project an automobile recycling system design was presented as well as an analytical model of the effect of system throughput on profits. The recycling system was based on the principles of Lean Production. Through a rigorous application of these principles, the number of buffers were reduced by half, system lead-time was reduced by approximately 78%, and an increase in effective throughput of 25% was achieved. Additionally, the lean system will lead to improved customer satisfaction, less damage to salable automobile parts, and less wear and tear on the forklift truck. Two key areas of future research were defined: 1) expand the scope of the system design to include more of the recycling process and 2) refine the current design through additional studies at greater depth.

The analytical model presented in this thesis related corporate profits to throughput (i.e. the number of vehicles recycled per unit time) assuming that the supply of vehicles to the facility is inelastic. Although the model presented herein contains some simplifying assumptions it provided three interesting and intuitive results. The first is if the total revenue excluding the sale of used parts exceeds the cost of purchasing and processing a vehicle, then all vehicles received should be processed. That is, the throughput should be maximized. The second is if the total revenue available from a vehicle including the sale of used parts is less than the combined costs of purchasing and processing a vehicle, then the throughput should be zero. Finally, if the total revenue available from a vehicle including parts-sales is greater than combined costs *and* the total revenue available excluding parts-sales is less than the combined then an optimal, non-zero, and finite throughput quantity exists.

To continue the modeling effort introduced in this thesis, two areas are suggested. The first is to expand the model to include such realities as supply elasticity. The second is to

conduct research aimed at establishing empirical values for the parameters introduced in the model. Efforts on both of these fronts will be great contributions to the automobile recycling industry.

Such projects are never possible without the support of others. In particular, the author wishes to thank Professor David Cochran, Director of the Production System Design Lab at MIT for his guidance and wisdom. The author also wishes to thank his wife, Tamara, for her love, support (to her the last 2 years seemed more like 5), and help putting up shelves. Although one may put up shelves alone, it is always more enjoyable to put up shelves with others. Finally, the author wishes to thank his sons, Jacob and Mason for always making him laugh. In the event that one or both of them read this document in the future (assuming they stop talking long enough to do so): Hi boys, thanks for taking an interest in your old man's work. Now, go clean up your room.

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Appendix A: Raw Data

Arrival Frequencies by Time of day and Date

Time	28-May	29-May	30-May	31-May	1-Jun	3-Jun	Total	Fraction
9:00-10:00	2	0	2	0	1	0	5	0.032258
10:00-11:00	2	1	4	0	2	2	11	0.070968
11:00-Noon	1	0	5	3	8	3	20	0.129032
Noon-1:00	2	4	3	2	4	6	21	0.135484
1:00-2:00	4	3	5	4	5	3	24	0.154839
2:00-3:00	6	3	2	6	6	4	27	0.174194
3:00-4:00	4	4	5	2	0	3	18	0.116129
4:00-5:00	4	4	1	1	1	4	15	0.096774
5:00-6:00	0	1	0	0	2	3	6	0.03871
6:00-7:00	0	7	0	0	1	0	8	0.051613
							155	1

Vehicles Purchases Broken Down by Type

Date: June 27, 1997 thru August 24, 1997

GM	FORD	DODGE	IMPORT
12	3	4	6
14	8	2	2
12	3	5	6
10	7	4	4
12	6	2	6
9	7	3	7
7	8	5	6
10	6	3	5
12	6	5	3
13	7	1	5
14	4	6	2
5	10	6	5
9	4	6	7
14	4	1	7
11	4	7	3
5	6	8	7
10	9	4	3
14	6	3	3
15	6	3	2
7	6	7	6
14	3	4	5
8	7	3	5
7	7	6	6
10	3	4	9
7	4	6	5
10	9	3	4
10	7	4	5
10	5	3	8
8	2	7	5
6	6	7	7
9	7	6	4
10	7	4	5
11	5	4	6
13	3	4	6
9	5	2	10
6	4	5	8
13	5	3	4
9	4	5	8
14	4	0	6
11	9	2	4
9	6	4	7
5	4	7	4
11	2	6	6
8	8	6	4
9	8	5	4
7	8	6	5
4	8	7	7
10	4	2	3
8	4	6	8
11	3	5	5
7	5	7	7
8	4	3	10
12	2	7	5
10	6	4	6
12	5	4	5
13	2	6	5
11	4	3	2
3	0	0	4
3	1	0	3
5	2	0	0
2	0	2	0
5	1	0	2
10	3	1	4
0	0	1	0
2	1	0	1
1	0	0	0
1	0	0	0
11	4	1	2
6	5	1	3
1	0	0	0
2	1	0	3
2	3	1	1
1	1	3	1
1	0	0	0
9	5	4	1
4	3	0	4
7	4	6	2
2	3	0	0
2	4	3	8
2	0	0	2
0	0	1	1
4	5	7	0
3	3	0	2
4	1	3	7
9	6	3	4
5	1	2	1
4	2	4	4
3	1	0	2
4	2	1	3
6	2	3	0
9	7	1	6
1	5	4	2
4	1	0	1
2	1	0	2
5	2	3	5
11	3	3	3
9	7	3	7

Total	481	278	216	263	1238
	GM	FORD	DODGE	IMPORT	
Proportion	0.3885	0.2246	0.1745	0.2124	1

Measured Times for Processes in the Drain-Shop of the Current System

Date:	August 27, 1997	August 27, 1997	August 27, 1997		Jan. 05, 98	Jan. 05, 99	August 27, 1997	August 27, 1997	August 27, 1997	August 28, 1997	August 27, 1997
Function:	Ground Operations (required time only)	Rack Operations (required time only)	Gas Tank Operations (required time only)	Total Time Required to Drain	Time Requied to Drain	Storage Time on Rack	Shuttle Imports to 60' Road	Set Imports on Stands	Imports Take Down	Draining Completion Rate	Transport Crusher to Pile
Time:	2:29	6:46	1:29				1:20	1:57	1:09	10:46	
	3:13	5:43	2:32				1:17	1:23	1:15	9:45	1:04
	3:25	6:56	2:43				1:24	1:44	1:20	13:55	
	3:28	5:59	1:22		1:22		1:20	1:43	1:11	10:16	1:15
	4:01	9:12	1:49						1:18	8:58	
	4:25	7:25	1:55						1:14	13:45	
	4:37	8:33	2:11		1:14	9:28	1:14	1:43	1:15	12:51	
	5:44	6:34	2:00					1:46	1:13		
	5:53	6:04	1:20		0:22	9:23	1:13	1:20	1:13	7:18	1:05
	6:06	5:40	2:04						1:20	16:24	
			1:15								
Mean:	4:20	6:53	1:52	13:06	0:59	9:25	1:18	1:39	1:14	11:33	1:08
Standard Deviation:	1:14	1:11	0:27		0:32	0:03	0:04	0:13	0:03	2:52	0:06

Decimal Mean	4.33
Decimal Std Dev	1.23

Appendix B: Technical Appendix

Lead-Time Estimate

The estimation of 3.5 days is based on the following: in the current schedule, vehicle types (GM, Ford, Chrysler, Import) are only processed once per week by the set-up team. Thus, using the assumption that vehicle arrivals are random, vehicles will spend an average of 0.5 weeks in the post-drain buffer. Mathematically, this may be proven as follows:

Consider only one type of vehicle. Let

P(d)= probability that a vehicle will arrive a particular day of the week,

T= the day of arrival,

W= waiting time in the post-drain buffer, and

t_*=day on which vehicles are removed from the post drain buffer.

Then,

$$W = t_* - T \tag{B-1}$$

If we begin the week at time zero (i.e. T=0), then the post-drain buffer is emptied on day seven (i.e. t_*=7) since the post drain buffer is emptied once per week. The expected, or average, time in the buffer is described by

$$E[W] = \int_0^7 (t_* - T) * P(d)dT \tag{B-2}$$

Assuming that vehicles are no more likely to arrive on any one than on any other, the probability of arrival on any one day, P(d), is 1/7. Thus,

$$E[W] = \int_0^7 (7 - T)(1/7)dT \tag{B-3}$$

$$E[W] = [T - T^2/14]_0^7 \tag{B-4}$$

$$E[W] = 3.5 days \tag{B-5}$$

Pre-Crush Person Time Calculation

The following calculation was used to determine the amount of time spent on pre-crush activities by the pre-crush person. All data relating to time estimates were provided by the pre-crush person and are assumed to be reasonable. The average number of vehicles processed per day by the drain-team was obtained from management data at the Calgary facility and is based on the total annual production.

	Test Data			Extrapolated			
Make	Number of Vehicles Processed	Time (min)	Average Time (min/vehicle)	% of Type Processed per week	Number Processed per week	Spent per Week (min)	Spent per Week (hrs)
GM	10	20	2	0.3959	87.73	175.47	2.92
Ford	10	30	3	0.2164	47.95	143.86	2.40
Imports	10	20	2	0.1714	37.98	75.96	1.27
Chrysler	10	15	1.5	0.2164	47.95	71.93	1.20
						Total	7.79

Average Number of Vehilces processed per day in drain-shop= 31.66
Calculated Number of Vehicles Processed er week= 221.62

Centroid of Row Calculation

Consider the row shown in Figure B-1 below. For each vehicle (shaded region) to the left of the center there is a vehicle equidistant to the right of the center. Since both vehicles are the same distance from the center of the row, the total distance traveled to both vehicles is twice the distance to the center of the row. A similar argument applies to each pair of vehicles in the row centered about the row midpoint. Thus the total distance traveled in filling the row is the product of the number of vehicles in the row and distance from the edge of the row to the row midpoint.

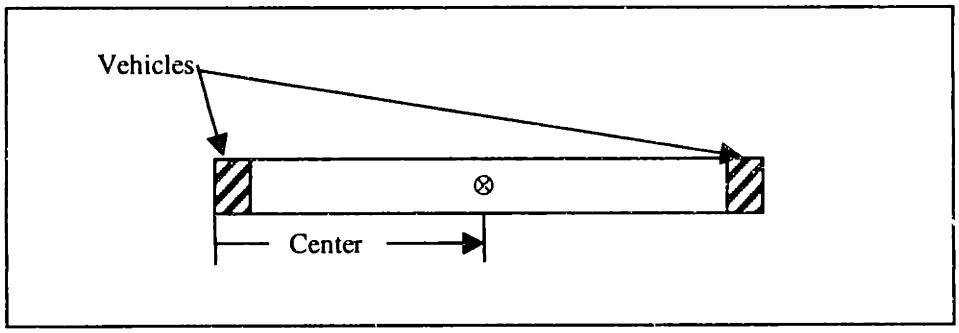

Figure B-1. Typical row layout.

Appendix C: Network Model

Data

Row No	1	2	3	4	5	...	62	Unused Rows
Distance from drain-shop	475	488.3	501.6	514.9	528.2	...	1418	0
No of vehicles in row	17	17	17	17	17	...	38	10000
Total Distance in Filling Row	8075	8301.1	8527.2	8753.3	8979.4	...	53884	0

Decision Variables

	x11	x12	x13	x14	x15	...	x457	x458	x459	x460	x461	x462	1-Unused Rows	2-Unused Rows	3-Unused Rows	4-Unused Rows
Assignment																

Flow Balance Constraints

Node	x11	x12	x13	x14	x15	...	x457	x458	x459	x460	x461	x462	1-Unused Rows	2-Unused Rows	3-Unused Rows	4-Unused Rows	Dot Product	sign	S
1	1	1	1	1	1	...	0	0	0	0	0	0	1	0	0	0		=	62
2	0	0	0	0	0	...	0	0	0	0	0	0	0	1	0	0		=	62
3	0	0	0	0	0	...	0	0	0	0	0	0	0	0	1	0		=	62
4	0	0	0	0	0	...	-1	-1	-1	-1	-1	-1	0	0	0	1		=	62
1	-1	0	0	0	0	...	0	0	-1	0	0	0	0	0	0	0		=	-1
2	0	-1	0	0	0	...	0	0	0	-1	0	0	0	0	0	0		=	-1
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮		⋮	⋮
62	0	0	0	0	0	...	0	0	0	0	0	-1	0	0	0	0		=	-1
Unused Rows	0	0	0	0	0	...	0	0	0	0	0	0	-1	-1	-1	-1		=	-186

Fraction Constraint

Type	Value	sign	Constraint
1		>=	475
2		>=	250
3		>=	250
4		>=	200

Objective Function

Total Distance=

Notes.
To prevent infeasible solutins and because the number of vehicles wtin any row is fixed, the fraction of vehicles by type is constrained at some value less than the true fraction

The dot product is the sum of the products of the terms in the Assignmnet and Node vectors

To keep the spreadsheet a manageable size, portions of teach matrix is shown