Development of a Tool Control and Process Information System to Support Low-Volume Automobile Assembly

by

James Arthur Bowen

B.S., Mechanical Engineering
Cornell University, 1992

Submitted to the Department of Mechanical Engineering and
to the Sloan School of Management
in Partial Fulfillment of the Requirements for the Degrees of

Master of Science in Mechanical Engineering

and

Master of Science in Management

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Abstract

Most automobiles produced in the world today are built in volumes in excess of 50,000 units per year. There are a number of benefits to producing vehicles in lower volumes, but current production methods are cost inefficient in building vehicles in annual volumes less than 30,000 units. Vehicle production in these volumes requires new production tools and processes in an number areas.

The tools used for securing threaded fasteners in automobile final assembly do not perform well in low-volume production scenarios. A new tool system was developed explicitly for low-volume production usage. This new system has several benefits compared to traditional systems when used in low-volume production. Chief among these benefits are improved quality and flexibility of the tools and production system.

Thesis Advisors: Kevin Otto, Assistant Professor of Mechanical Engineering
Donald Rosenfield, Senior Lecturer, Sloan School of Management

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Table of Contents

1. Introduction

The majority of automobiles produced in the world today are built in annual volumes in excess of 50,000 units. Many of these vehicles are assembled by manufacturers with total production in excess of one million units per year. Yet, some of these mass producers and mass marketers are investigating the potential of building vehicles in significantly lower volumes. In doing so, these manufacturers are venturing into an entirely new area of vehicle production. These same manufacturers are discovering their high-volume production expertise is not applicable to low-volume vehicles. This has forced these high-volume manufacturers to re-evaluate their methods of vehicle production to discover an efficient means of building vehicles in low-volumes. In researching this thesis, I was involved in one such re-engineering program at a major U.S. automobile manufacturer, hereafter referred to as the Zeta Motor Company. My work at Zeta concentrated on developing new tools and systems to aid in low-volume automobile assembly. This thesis will document these efforts.

1.1 Thesis Summary

This thesis will explore the interesting area of low-volume production in two parts. First, it will present a summary of the strategic reasons for a high-volume manufacturer to produce a low-volume vehicles (Chapter 2). This part will also explain some of the impediments which resist these efforts (Chapter 3). I will soon show that overcoming these impediments is the principal focus of high-volume manufacturers exploring low-volume production. This first part of my thesis will conclude that the potential benefits derived from low-volume production are significant enough to warrant efforts to overcome the impediments.

The second part of this thesis will document one aspect of the effort undertaken at Zeta Motor Company to design a low-volume automobile assembly system. This effort concentrated on developing improvements to the tools, processes and control systems used in the final assembly area of an automobile assembly plant. This thesis will explore the development of a flexible-torque nutrunner system for securing threaded fasteners in a low-volume production system. As a motivation for this part of the thesis, Chapter 4 will explain the importance of threaded fasteners to vehicle assembly. This chapter will also exemplify why current fastening tools and systems don not operate effectively in low-volume production. Following this, Chapter 5 will detail the development methods used in designing this new system. Chapter 6 will then provide a summary of the key attributes of this system and compare it to the existing systems presented in Chapter 4. This comparison will be continued into Chapter 7 which will provide quantitative evidence how the newly designed system is better suited for low-volume vehicle production.

The remainder of this chapter will provide an overview of the current automotive industry in order to better understand the contrasts between high-volume and low-volume production. Specifically, I will demonstrate that while high-volume producers dominate in industry, low-volume vehicles are becoming more common. In addition, I will explain the predominate ways. However, to start off I will provide some definitions of key terms needed to anchor later discussion.

1.2 High and Low-Volume Vehicles Defined

The preponderance of automobiles produced in the world can be considered high-volume or mass-produced vehicles. At the same time, there are a number of vehicles which are produced in volumes significantly lower that can be best termed low-volume vehicles. However, classifying a vehicle as either high-volume or low-volume can be difficult. Simply classifying a vehicle based on a single year's production can lead to problems. For instance, new vehicles are typically produced in lower volumes in their first year of production due to "ramp-up" production schedules. Likewise, a vehicle produced in high volumes in the past may experience a noticeable drop in production if sales decline significantly. In either case, a true high-volume vehicle could be mistakenly interpreted as being low-volume vehicle. In order to alleviate this potential ambiguity , I have adopted the following definitions:

Low-Volume Vehicle:	A vehicle produced for sale to the public for which annual production volumes are less than 30,000 units for every year the vehicle is produced.
High-Volume Vehicle:	A vehicle produced for sale to the public for which annual production volume is greater than 30,000 units in at least one year of production.

It is important to note two details of these definitions. The first is that these vehicles are produced for sale to the public. In making this stipulation, I seek to exclude prototypes, show cars and engineering test vehicles from being considered low-volume production vehicles. These pre-production vehicles are built by almost every manufacturer during the development of new high-volume vehicles, yet are not intended to be sold to the public. As such it would be improper to include such vehicles in this study.

The second detail to note is the 30,000 unit threshold value chosen to delineate the difference between high and low-volume vehicles. Though there is a certain arbitrary nature to this number (35,000 or 40,000 may be an equally suitable number), it is based on observed differences in vehicle production. Below 30,000 units per year there are a number of methods employed for vehicle production, while above this volume only minor variations of traditional high volume production are employed. As this thesis concentrates on the manufacturing aspects of low-volume vehicles, this definition seems most suitable. With these definitions of high-volume and low-volume vehicles in hand, it is possible to perform a brief analysis of the world automotive industry with respect to high and low-volume vehicles. This is done in section 1.3 below.

1.3 Annual Production Volumes in the Automotive Industry

In 1991 over 46 million passenger cars and commercial vehicles were produced by over a hundred manufacturers around the world. As shown in table 1.1, three-quarters of this volume can be attributed to the twelve largest manufacturers, who produce over a million vehicles apiece. Not surprisingly, the bulk of the vehicles produced by these manufacturers are high-volume vehicles.

Company	Volume	Company	Volume
General Motors	6,634,735	Daimler Benz	861,198
Ford	5,138,360	Hyundai	795,291
Toyota	4,511,219	VAZ	687,000
Volkswagon	3,088,433	Daihatsu	670,481
Nissan	3,025,759	Fuji	644,630
PSA	2,467,227	BMW	536,003
Renault	2,004,237	Isuzu	470,950
Honda	1,908,764	Kia	425,296
Fiat	1,898,555	Rover	419,907
Chrysler	1,674,289	Volvo	343,089
Mitsubishi	1,595,075	GAZ	268,000
Mazda	1,551,255	Daewoo	203,792
Suzuki	912,778	*Other manufacturers:*	*3,760,108*

Table 1.1 Annual Vehicle Production for Top 25 Manufacturers (1991)
[Source: American Automobile Manufacturers Association]

To present a more meaningful analysis of the automobile industry, the remainder of the thesis will emphasize automobile manufacturers located in one of three regions: North America (US & Canada), Western Europe, and Japan & Korea. This group of manufacturers account for 91% of total world vehicle production and represents a valid sample of the global automotive industry. There are two reasons for excluding manufacturers in other regions and manufacturers producing exclusively commercial vehicles. First, manufacturers in other regions are in a different development stage of their automotive industry. The typical vehicle built in third world regions does not comparable to vehicles built in these three regions in terms of quality and product features. As such it would not be proper to compare vehicles between these regions in this study. Second, exclusive commercial vehicle manufacturers, as opposed to exclusive automobile manufacturers or manufacturers building both automobiles and commercial vehicles , have significant enough product differences to justify excluding them from this study.

Figure 1.1 shows a histogram of vehicle volume by platform*, in order to present an understanding of the vast number of high-volume vehicles compared to low-volume vehicles, As shown, out of 44 platforms in production in American and Canadian plants in 1992, only six fall below the 30,000 unit per year defining volume. However, further investigation of these six vehicles shows that two are produced in high-volume in other plants in the world, and one was produced in high-volumes in previous years. Thus, only three vehicles built in the US and Canada in 1992 can be classified as low-volume vehicles by my definitions. These vehicles are the Dodge Viper (171 units), Cadillac Allante (1,985) and Chevrolet Corvette (21,580). [AUTOFACTS, 1993]

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* A vehicle platform refers to a collection of vehicle models sharing a common body structure with only minor differences between each model. One example of a shared platform is the Ford Taurus platform which provides the basis for both the Taurus and Mercury Sable

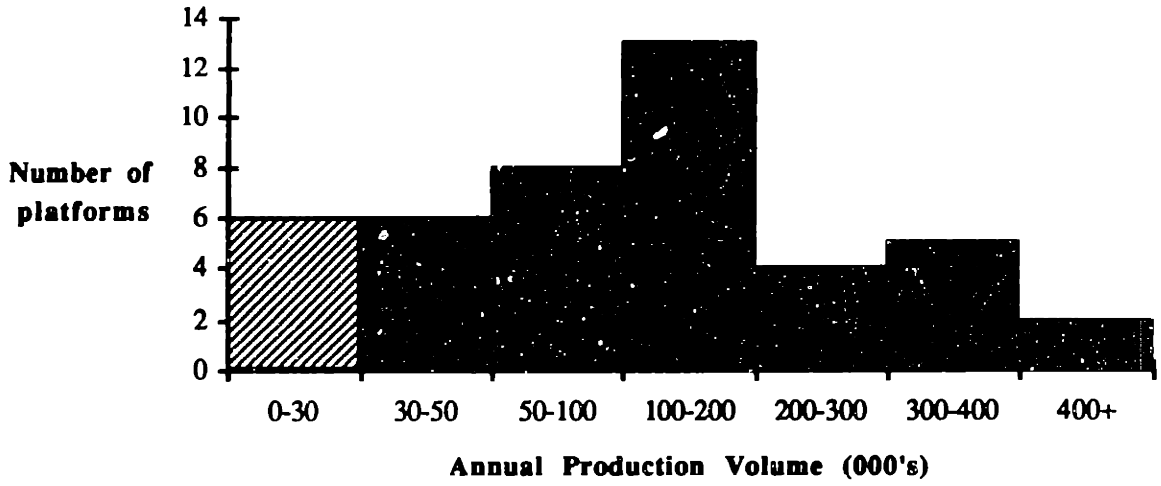

Figure 1.1 **Annual Production Volume by Platform (North America, 1992 MY)**
[Source: AUTOFACTS, 1993]

Figure 1.2 shows a similar breakdown of vehicle production volumes - this time as percent of total production versus platform production volume. As shown, the six vehicles produced in volumes of less than 30,000 units represent less than 1% of total North American production. An identical analysis of Western European and Asian (Japan and Korea) production would show similar results: the number of low-volume vehicles built in the world is far less than the number of high-volume vehicles in both volume and number of platforms.

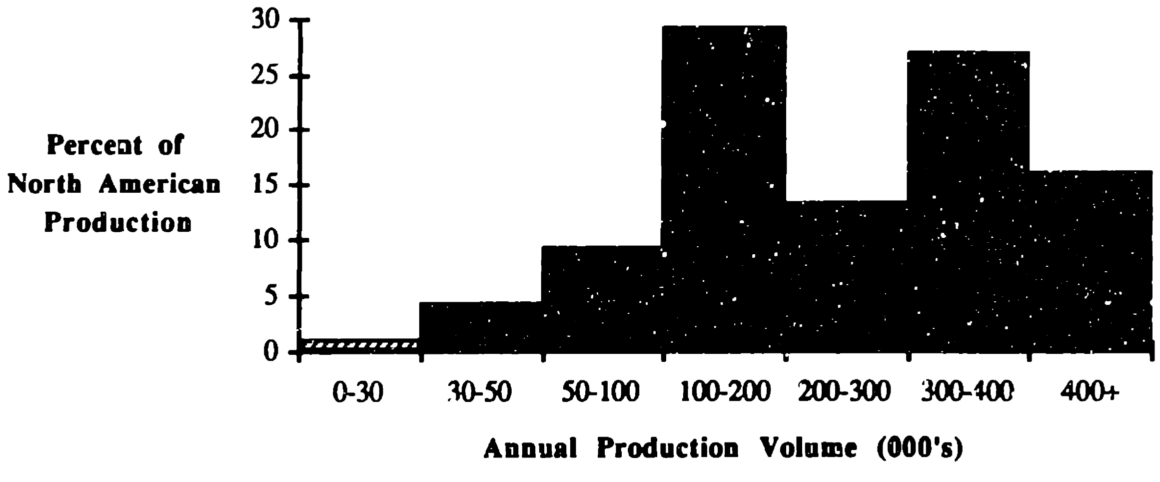

Figure 1.2 **Annual Volume by Percent of N. American Production (1992 MY)**
[Source: AUTOFACTS, 1993]

1.4 The Automotive Industry - High and Low-Volume Manufacturers

The previously presented Table 1.1 presents a somewhat biased view of the automotive industry regarding the characteristics of the companies producing motor vehicles in the world. From this data one might expect that all manufacturers build hundreds of thousands (or even millions) of vehicles each year. This is far from the truth. Several manufacturers produce less than 10,000 vehicles per year for the entire company. In order to understand the structure of the automotive industry with respect to these tremendous differences between manufacturers, it is necessary to classify vehicle manufacturers as either exotic, low-volume or high-volume manufacturers. This is done in the following manner:

Exotic producers:	Manufacturers producing less than 100 vehicles per year. Included in this category are companies which make performance modifications to existing high-volume vehicles and companies specializing in converting gasoline powered vehicles to electric power. Examples include: AMG, Bertone, McLaren, and Saleen
Low-volume producers:	Manufacturers producing over 100 vehicles per year with each vehicle being a low-volume vehicle (i.e. model production volumes are less than 30,000 units/yr.). Examples include: Aston Martin, Ferrari, Jaguar and Lamborghini
High-volume producers:	These are are manufacturers for which the vast majority of their business is involved in high-volume vehicle production, though they may produce a limited number of low-volume vehicles. Examples include: BMW, Chrysler, Honda and Volkswagon

With these manufacturer classifications it is possible to perform a more accurate study of the automobile industry's manufacturers. Figure 1.3 shows a breakdown of all vehicle producers in Western Europe, Japan & Korea and North America. As one can see, the number of firms classified as either exotic or low-volume producers dramatically outnumber the number of high-volume producers.

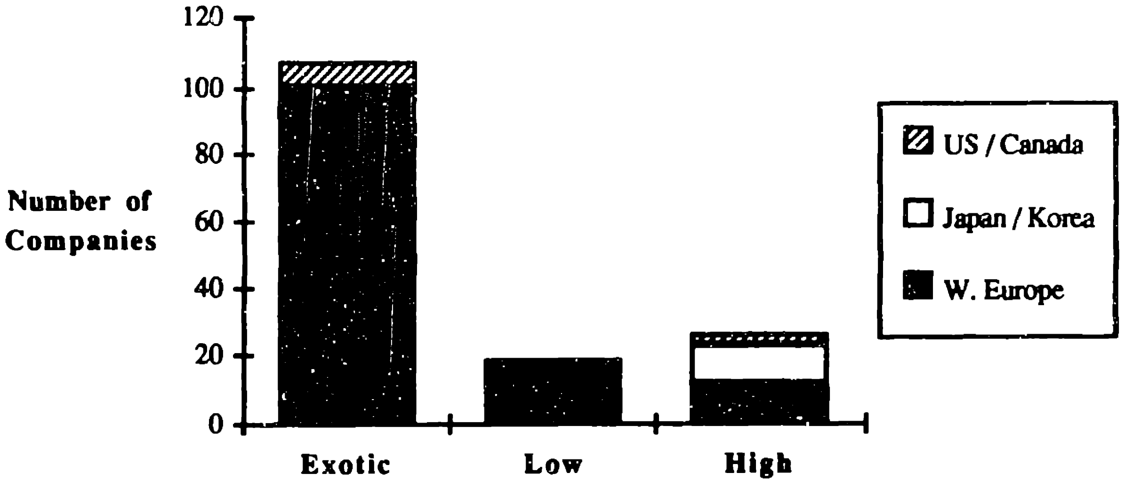

Figure 1.3 Worldwide Vehicle Manufacturers by Type
[Source: Auto Katalog, 1993]

However, from the following table of production volumes, one can see the total number of vehicles produced by high-volume producers is far larger than the number of vehicles produced by either exotic or low-volume producers.

Manufacturer Type	Production Volume (1991)
High-Volume Producers	42,070,501
Low-Volume Producers	101,990
Exotic Producers (est.)*	10,700

Table 1.2 Annual Production Volume by Manufacturer Segment
[Sources: AAMA, Auto Katalog]

Beyond this enormous difference in production volumes, there are other significant distinctions between these types of manufacturers. The most important distinction involves the manufacturing methods used by these different types of producers. Exotic manufacturer production can be best described as "job shop" production due to the very short product lifetimes and low annual production volumes. High-volume and low-volume manufacturers also use distinctive manufacturing methods, yet these methods share more in common with each other than with exotic production methods. As the core goal of my research was to

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* Total exotic manufacturer volume is approximate based on 107 identified firms and a maximum of 100 vehicles/firm/year.

investigate low-volume production from the viewpoint of a high-volume manufacturer, I will concentrate on the later two classifications, high-volume and low-volume producers. Exotic manufacturers will be excluded from the remainder of this text for this reason.

1.5 High and Low-Volume Production Methods

As stated in the previous section, high-volume and low-volume manufacturers use different methods to produce automobiles. These differences are one of the key distinguishing factors between high-volume and low-volume vehicles. For this reason, I present a brief overview of the most predominant methods of high-volume and low-volume automobile assembly.

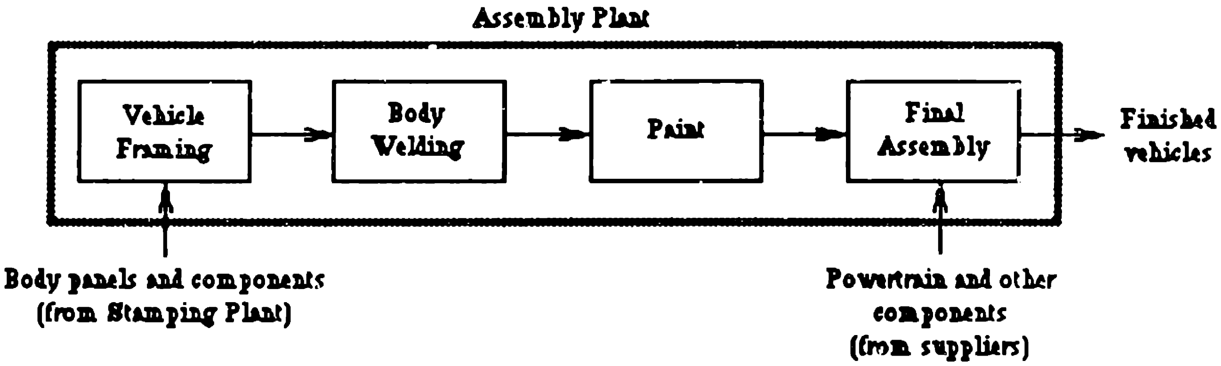

Figure 1.4 Schematic View of Automotive Assembly

Figure 1.4 presents a simplified schematic of the major components of automobile assembly. As the diagram shows, the assembly process is roughly sequential with four distinct elements:

Vehicle Framing:	Stamped steel body components are located by fixtures and spot welded to maintain their orientation.
Body Welding:	All remaining structural components are placed in position and the entire body structure is welded.
Paint:	The completed body structure is cleaned, primed, painted and then baked dry.

Final Assembly:	All remaining components are assembled and installed on the vehicle. This includes powertrain, suspension, glass, wiring, interior and exterior trim and all other non-structural components. Following assembly the vehicle's major systems are tested.

High-volume manufacturers typically use very similar methods in producing their vehicles. Buzacott [1990] characterizes high-volume automobile assembly systems as having the following attributes:

- Mechanical conveyors moving vehicles at a uniform speed
- Fixed time available for worker to perform assembly tasks
- Nearly constant sequence of vehicle throughout the system
- Off-line repair of defects and assembly errors
- Minimum inventory banks between segments of the line

A direct result of these characteristics is a high degree of specialization of tasks among the assembly line operators. In a traditional high-volume assembly line, the typical worker is assigned to a certain location on the line (i.e. a work station) and responsible for performing only a small number of tasks. The worker will then repeat these same tasks for each vehicle built with only minimal differences based on the individual vehicle option content.

The desire to increase the throughput of such systems has led to a similar attribute of modern high-volume automobile assembly: widespread use of highly specialized equipment. This equipment can either replace a worker or reduce the time a worker requires to perform a task. In many instances this equipment can only be used for a single operation and/or for a specific vehicle model. Due to this specialization, most high-volume systems are well suited for producing several thousand nearly identical products annually. However, these systems often lack the flexibility to deal with diverse products and low production volumes.

Low-volume vehicles, on the other hand, are currently built by a number of different production methods. Three common methods are "blend-building" with a high-volume vehicle, building on a dedicated low-volume assembly line, and hand-built or "craft" production. Each method will be discussed in further detail below.

Blend-building

Blend-building involves assembling several distinct vehicles on the same assembly line, typically a high-volume assembly line. The vehicles built on this line may be either low-volume or high-volume vehicles, depending on their individual production volume. This form of production is favored in the production of high-volume derivatives.* The similarities between these vehicles allows them to be built on the same assembly line. The more distinctive the vehicles are (i.e. fewer shared components) the more difficult it becomes to produce multiple vehicles simultaneously. In such a case the assembly line is often optimized for the highest volume vehicle, with the low-volume vehicle(s) being built in a less efficient manner. Examples of high-volume derivatives include most convertible versions of high-volume vehicles as well as heavily modified high-performance versions of high-volume vehicles (e.g. Ford Taurus SHO). In some instances, the low-volume vehicles will be only partially assembled on the main assembly line. These vehicles are then completed either at an off-line assembly area within the assembly plant or out-sourced to a specialist company.

Dedicated low-volume assembly line

A dedicated low-volume assembly line uses similar methods to a high-volume assembly line. Like high-volume assembly lines, these low-volume systems typically use moving conveyors to transport vehicles to operators assigned to a certain station and responsible for certain assembly tasks. The most important distinction between these two assembly lines is the longer cycle time of the low-volume assembly line that results from the lower throughput (i.e. production volume). Whereas a high-volume assembly plant will have cycle times of a minute or less, a dedicated low-volume assembly line can feature cycle times of five minutes or more. This increase in cycle time means each worker is typically responsible for many more operations on each vehicle than his high-volume counterpart. In addition, for reasons discussed in Chapter 3, low-volume assembly lines cannot use highly specialized equipment as effectively as high-volume assembly lines. As such, low-volume lines frequently use far less automation and more manual labor than high-volume assembly lines.

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* A high-volume derivative is a low-volume vehicle which shares a significant number of parts with a high-volume vehicle to allow them to be built on the same assembly line simultaneously. Most often such vehicles will be derived from the same platform and share almost all body structural parts.

Craft production

The final method of low-volume vehicle production, craft production, harkens back to the early years of the automobile industry. In craft production, a very low number of high-skilled "craftsmen" build the vehicles from the ground up. The number of operations each worker is responsible for is enormous compared to an assembly line based production method. For instance, at Aston Martin one of five engine builders will spend an entire week building a single engine.[Hooper, 1987] This form of production is typically used by exotic manufacturers and high priced low-volume producers such as Aston Martin, who can afford to charge hefty prices to outweigh the exorbitant labor costs involved in this production method.

The basic characteristics of these four types of automobile assembly are summarized in Table 1.3 below.

	Traditional high volume production	Blend build with high volume models	Dedicated low volume assembly line	Hand built craft production
Specialized tooling	High	High - medium	Medium	Low
Average worker minutes per car	< 1.5 min	< 1.5 min*	2 - 10+ min.	Hours - days
# of products per assembly line	Low	Several similar vehicles	One - several distinct vehicles	One - several distinct vehicles
Total line volume	> 30,000	> 30,000	500 - 30,000	< 500

Table 1.3 Common Automobile Assembly Methods

1.6 Conclusion

So far this chapter has presented an industry-wide view of high and low-volume vehicles. Before embarking on a more detailed analysis of low-volume vehicle production in the upcoming chapters, it is would be beneficial to include a list of notable low-volume vehicles produced in recent years. Table 1.4 presents such a listing of twenty low-volume vehicles produced by both low-volume and high-volume manufacturers. Included in this table is the peak production volume for each vehicle during the years 1989 to 1993 and the

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* Excepting off-line or out-sourced work.

year in which this peak occurred. This table is not meant to be all inclusive; instead it represents a sampling of some of the world's low-volume vehicles. Some of these vehicles will serve as examples in the following chapters.

Vehicle	Peak Production Volume	Year
Low-volume Producers		
Aston Martin Virage	171	1990
Ferrari Mondial	863	1989
Ferrari 348	2,317	1991
Jaguar XJS	10,979	1989
Jaguar XJS-R	578	1990
Lamborghini Diablo	607	1991
Lotus Elan	2,060	1991
Porsche 911	20,855	1990
Porsche 968	4,937	1992
Rolls Royce Phantom	863	1989
High-volume Producers		
Acura NSX	8,422	1991
Audi A8	20,000	(projected)
BMW 850i	9,517	1991
Buick Reatta	7,253	1990
Cadillac Allante	3,726	1990
Chevrolet Corvette	22,578	1993
Dodge Viper	1,961	1993
Mazda RX-7	26,654	1992
Toyota MR2	25,234	1991
Volkswagon Scirocco	8,865	1989

Table 1.4 Notable Recent Low-Volume Vehicles
[Sources: AAMA, AUTOFACTS, Auto Katalog, Japanese Automotive Industry Yearbook]

This chapter has shown there is a small, yet significant number of low-volume vehicles built in the world every year. These vehicles are built by both companies specializing in low-volume vehicles (low-volume producers) and companies which concentrate on high-volume vehicles (high-volume producers). In addition, these vehicles are built using a number of different production methods, each with its own advantages and limitations. Clearly with so many manufacturers producing low-volume vehicles, there must be some advantages of such vehicles relative to their high-volume brethren. The next chapter will provide an overview of some of these benefits. Specifically, it will address the question of what benefits low-volume vehicle production can provide a high-volume manufacturer such as Zeta Motor Company.

2. Strategic and Business Justifications for Low-Volume Vehicles

Prior to beginning an investigation of methods by which a high-volume automobile manufacturer can produce low-volume vehicles, it will prove insightful to consider the benefits of such vehicles. There are four principle benefits low-volume vehicle production can provide high-volume automobile producers as an extension of their high volume business. These benefits are the following:

- Low-volume vehicles allow for greater segmentation of the automobile market
- Low-volume vehicles can improve consumer perception of a company's entire product line of vehicles leading to sales gains in its high-volume business.
- Low-volume vehicles offer distinct advantages in developing new process technologies for use in future high-volume vehicles.
- Low-volume vehicles may be necessary to satisfy certain future government regulations.

High volume automobile manufacturers who are currently marketing or considering marketing low volume vehicles have likely justified their investments through one or more of these reasons. The underlying reasons why low-volume vehicles provide these four benefits may not be immediately obvious. For this reason the following sections will provide a more detailed explanation of mechanisms behind each of these benefits.

2.1 Using Low-Volume Vehicles to Compete in Smaller Market Segments

One of the most often sited reasons for producing low-volume vehicles is to satisfy the demand of a very small market, often called a "niche market." Many people in the industry believe these markets can be highly profitable due to the higher prices such exclusive vehicles can command. However, there is current little research available to justify this claim. In the remainder of this section I will attempt to prove that such small market segments can be very profitable - especially for the firm marketing the first product in such a market (i.e. the "first mover").

The world automotive market is composed of a highly heterogeneous collection of customers and customer preferences. As such, one can envision the entire market as being subdivided into a collection of market segments, each containing a (more) homogeneous collection of customer preferences. High-volume manufacturers have typically targeted those segments which offer the highest potential for sales, ignoring segments with fewer potential sales. The ability to produce automobiles in low volumes provides an opportunity for a high-volume producer to enter, compete in, and profit from these smaller market segments.

Market segmentation and perceptual maps

The benefits of a market segmentation strategy are well known both within industry and in academic literature. The basic premise of market segmentation is that heterogeneous markets are better served by several distinct products catered to individual segments rather than a single generic product serving all. Evidence of this strategy being used within the automotive industry can be seen in the diversity of models produced by most high-volume manufacturers. However, it is important to note each of these distinct models is produced for segments which allow these manufacturers to use their time-proven high-volume manufacturing processes and plants. In other words, the anticipated sales within a market must be larger than the break-even volume associated with the high-volume production methods and facilities used. The question then arises: what about the smaller markets in which high-volume manufacturers have traditionally abstained from competition?

By using perceptual mapping*, it is possible to demonstrate the relationship between these different sized markets and the production volumes of vehicles serving them. A perceptual map allows products to be located relative to each other along an attribute axis. Using this same it is possible to plot a population graph of potential customers (see Figure 2.1). For the purpose of this discussion I will assume that most customers within this segment have similar preferences for key product attributes, with only a relative few customers having radically different preferences. From is assumption it is possible to represent the distribution of potential customers along a single attribute scale by a normal "bell-shaped" curve.

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* According to Urban and Hauser [1993], "Perceptual maps visually summarize the dimensions that customers use to perceive and judge products and identify how competitive products are placed on those dimensions." In perceptual mapping the key attributes affecting customer purchasing decisions become the axis for a plot describing the relative positioning of customers and products. In such plots, the closer a product is to a customer on a particular attribute scale, the more willing that customer is to purchase the product.

When this model is used, it can be shown that even in the absence of competitors a single product (designated "A") is often unable to satisfy all the consumers of the market segment (see Figure 2.1). For some customers the differences between the product attributes and their own preferences are such that their personal utility gained from purchasing the vehicle is less than the cost. These customers will not buy the vehicle and are represented by the non-shaded region. Customers in the shaded region find sufficient utility from the vehicle to be considered potential buyers. In such a scenario, the best product design is one which appeals to the largest number of potential buyers, as shown in the figure.

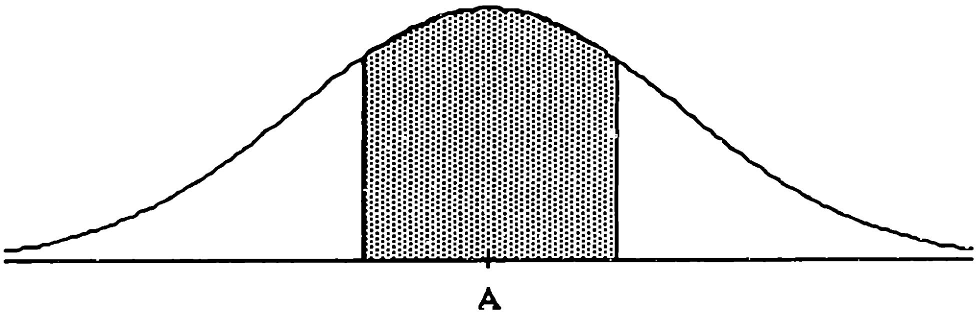

Figure 2.1 Perceptual Map of Market with one Product

In order to enlarge the number of potential buyers, current high-volume manufacturers typically build closely related sub-models. These sub-models are very similar to the base model but offer a slightly different set of attributes to the customer based on differences in body style, powertrain, or interior trim. This allows a single model to cover a larger area in the perceptual map of the segment as shown in Figure 2.2. However, technical constraints limit the amount of intra-product differentiation, and likewise the number of potential customers a single model can satisfy. The most notable of these constraints is the inability of most high-volume manufacturing systems to deal with design differences between vehicles built on the same line and the high values for break-even volumes for each sub-model.

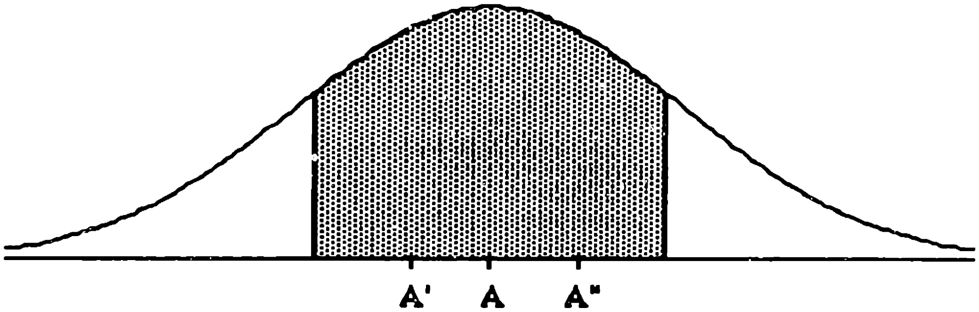

Figure 2.2 Map of market with one company and several sub-models

When one includes additional competitors in this model, one can see that each company attempts to differentiate itself from its competitors while still being perceptually located close to the bulk of the customers. In this manner the high-volume manufacturers cover an even larger portion of the market, yet still disregard the sparsely populated regions of the market. (i.e. the non-shaded region of Figure 2.3 below)

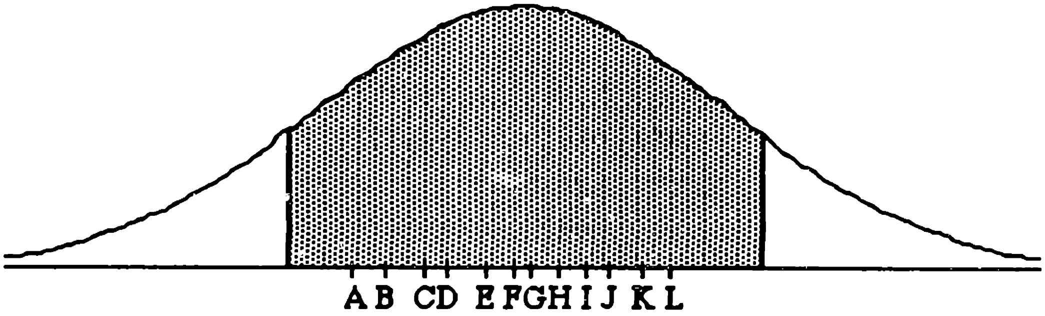

Figure 2.3 Map of market with several high-volume competitors

Market segmentation for Low-Volume Manufacturers

In contrast, a manufacturer with the ability to produce low volume vehicles cost effectively would be capable of producing products remarkably different from other products and exploit these nether-regions of the market segment. The inherent lower break-even volumes of such a manufacturing system would allow the manufacturer to locate products more distant from the densely populated regions of the perceptual map - and more distant from its purely high-volume competitors. This is illustrated by products X and Y in Figure 2.4.

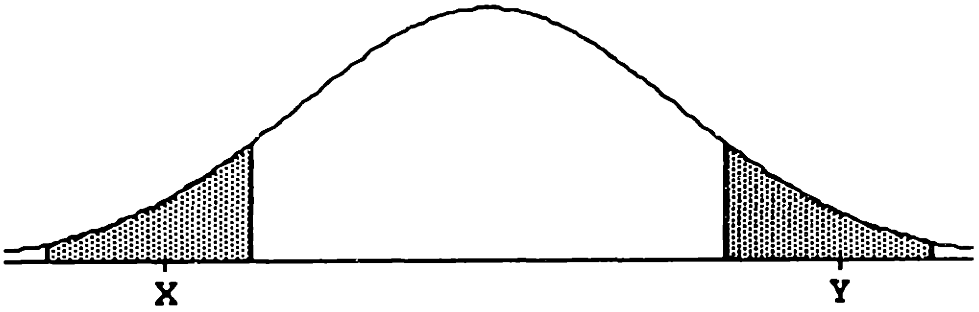

Figure 2.4 Marketing Possibilities for Low-Volume Vehicles

In this analysis it becomes clear there are two distinct regions of the market: a region where available products are limited by technology constraints and a region where products are limited by the tastes of the consumers (see Figure 2.5). In the central area the attributes of the products are limited by the inflexibility of high-volume manufacturing. If it were possible to build vehicles in lower volumes then the entire market could potentially be served. In this case, the only constraints on the range of feasible product offerings would be the preferences (or tastes) of the consumers.

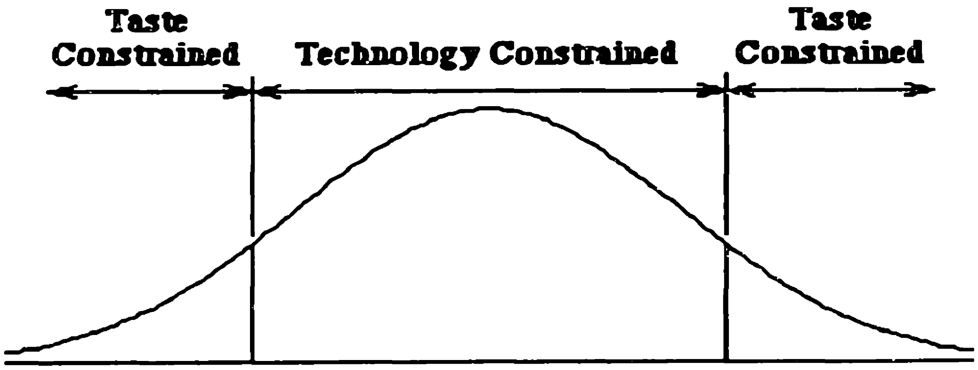

Figure 2.5 Different Forms of Market Segments

Dynamics of Taste and Technology Constrained Markets

Pepall [1992] provides an enlightening insight into the relationship of these two market segment types. Taste limited market segments, termed niche markets, occur when the range of buyer preferred products is smaller than the range of all technologically feasible (though not necessarily available) product. The opposite occurs in technology limited segments, which Pepall terms market niches. In her analysis she claims niche markets offer significant and sustainable first mover advantages which make it unprofitable for competitors to enter the niche and very profitable for the "innovating firm."

Pepall's rationale in making these claims is based on a simulation of two independent firms introducing two products into a previously unserved market segment. In this analysis, Pepall uses a parameter, α, to distinguish between these two types of markets. A value of α equal to 0.5 represents a market with only one feasible product type; a value of α equal to 2.0 represents a market in which the range of all feasible products is twice the range of customer preferences. Thus, low values of α represent technology constrained market niches, while high values of α represent taste constrained niche markets.

By determining the optimal product location along a single attribute scale for two companies - the first mover and the follower - Pepall is able to calculate the equilibrium prices, quantities and profits for each. This is shown in Figures 2.6 and 2.7 below.

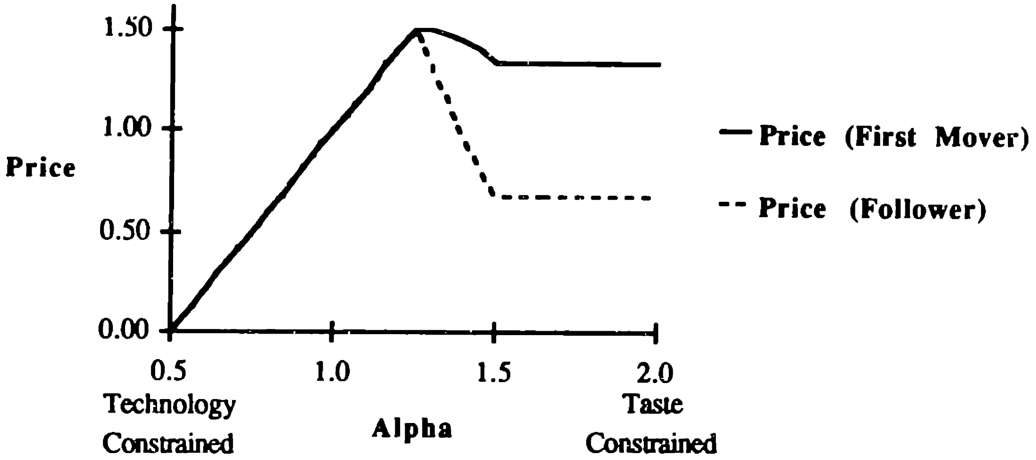

Figure 2.6 Price of Products vs. Market Type

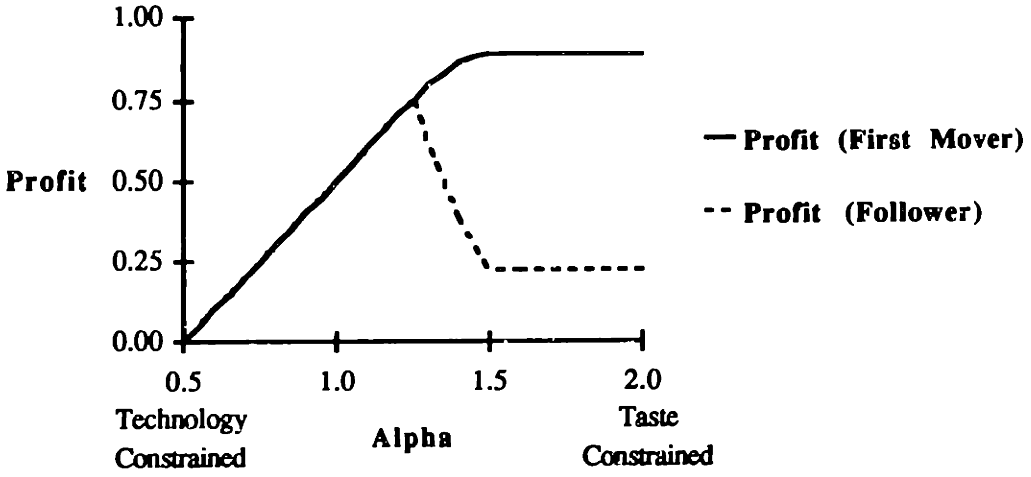

Figure 2.7 Profitability of Products vs. Market Type

As one can see, as the market becomes more constrained by customer tastes (i.e. alpha increases), the prices and profits of the first mover increase while the prices and profits of the follower decrease significantly. From this discussion, one can conclude that the taste constrained regions of the automobile market offer the potential for great profits for the first mover. Te key to becoming such a first mover relies on developing the ability to produce low-volume vehicles cost effectively.

2.2 Using Low-Volume Vehicles to Improve High-Volume Sales

A second reason for high-volume manufacturers to consider building low-volume vehicles is the indirect benefits marketing a distinctive low-volume vehicle can have on the sales of high-volume vehicles built by the same company. These benefits can take two forms: improved perception of the manufacturer as a producer of superior vehicles and improved awareness of the manufacturer's products. The end result of both effects can be increased sales of the company's high volume vehicles. A more detailed explanation of each of these potential benefits is possible by analyzing a commonly taught marketing model - the "lens" model.

The "Lens" Model

The lens model attempts to quantify the factors which enter a consumer's purchasing decisions. As shown in Figure 2.8, a consumers end choice is determined by a number of related factors. Obviously one of these factors is the physical features of the product and its competitors. However, according to the "lens" model, a customer's purchasing decision is also affected by his awareness of the product, the product's price, the consumer's perception of the product and other factors. For complex products (such as automobiles) where it is not possible for a person to easily evaluate all possibilities . the perception and awareness of a brand (or family) of products can become a surrogate for individual product perception and awareness.

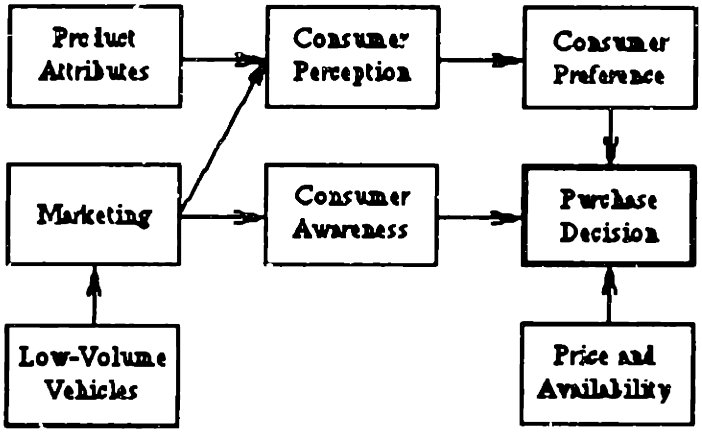

Figure 2.8 The "Lens" Model with Low-Volume Vehicles

Thus, selling a product to a consumer involves much more than merely building a product to suit his or her tastes in physical features or attributes. It also involves molding the potential customer's perception and awareness of the both the product and the brand. This is traditionally done through various marketing techniques such as advertising. However, a customer's awareness and perception of an automobile manufacturer's products can be improved by producing a low-volume vehicle.

Effects of Low-Volume Vehicles on Customer Awareness and Perception

A low-volume vehicle is capable of increasing a consumer's awareness of the company's entire brand simply by the attention such vehicles attract. The inherent uniqueness of such vehicles make them practically impossible to ignore on the highway, in the parking lot or in the driver's showroom. In addition, such vehicles typically receive a large amount of press coverage prior to their introduction. By associating these vehicles with an established high-volume brand name, all the attention garnered by these low-volume vehicles is also diverted to increasing the customer's awareness of the brand.

A low-volume vehicle is capable of improving a consumer's perception of the brand in a similar manner. A brief look at current low-volume vehicles (see Table 1.4) shows that almost all of these vehicles can be classified as either high-performance or luxury vehicles. By producing a vehicle capable of 200 mph or offering a silky smooth ride, the manufacturer is demonstrating its ability to tackle complex engineering and manufacturing problems in a successful manner. A consumer can look at these low-volume vehicles as a measure of what the manufacturer is capable of producing. Providing the customer looks favorably (or even better - in awe) at such vehicles then an improvement in the customer's perception of the entire brand logically follows.

By improving a brand's awareness and perception, a low-volume vehicle can aid the manufacturer in selling high-volume vehicles. Tom Kowalaski, Chairman of the Chrysler Motorsport Committee, states that this "image rub-off" is one of the biggest benefits of Chrysler's low-volume vehicle, the Dodge Viper [Stannard 1994]. Indeed this is likely the case for many low-volume vehicles produced by high-volume producers.

2.3 Using Low-Volume Vehicles to Develop New Technology

A third benefit of low-volume vehicles is their ability to help develop new technology for later use in high-volume vehicles. New technology is being introduced into automobiles at a rapid rate. The combined effect of global customer demands for better performance, improved fuel economy and safer vehicles mean that automobile manufacturers must continue to introduce new technologies to survive in the marketplace. As would be expected, the introduction of these technologies to a vehicle often requires extensive development of the engineering design prior to incorporation into a saleable vehicle. However, it is easy to overlook the fact that some of these technologies also require either modified or entirely new manufacturing processes in order to mass produce so-equipped vehicles. Viewed in this manner there are two forms of new technology development: product development and process development.

A key aspect of both product and process technology development involves testing engineering designs and manufacturing processes. In the early stages of technology development it is possible to conduct many of these tests in laboratory situations. Eventually, though, it is necessary to evaluate the new technology in actual vehicles. In traditional high-volume vehicle development, product development and process development are done in totally different manners.

Product development uses hand-built prototypes as a method of testing and evaluating new products and product technologies. Typically less than 50 prototypes are built per vehicle at an extreme cost of $0.3 to $0.6 million each.[Clark and Fujimoto, 1991] Many firms also use prototypes as a method of discovering process problems prior to production. However, the majority of process development is conducted through a pilot run. Clark and Fujimoto describe a pilot run as "a full-scale rehearsal of the commercial production system, including parts, tools, dies and assembly." Unlike prototypes, pilot vehicles are built in volumes between 50 and 200 units for each new vehicle, at costs several orders of magnitude lower.

The key to both forms of technology development is learning as much as possible regarding the new technology and its interaction with the rest of the vehicle prior to commencing high-volume production. The small number of pilot an prototype vehicles can be placed through the rigors of numerous tests to determine the system performance in a variety of conditions. From these few vehicles a tremendous amount of information can be gathered as feedback to the new product technology. Once the new technology has been researched and studied enough to the manufacturer's satisfaction, it can be incorporated into a high-volume production vehicle.

However, in cases where significant manufacturing process development is required, the small number of vehicles may not produce enough feedback. This is a result of the very small number of vehicles produced This may seem a contradiction to my previous statement that a small test fleet can provide enormous amounts of product technology feedback - it is not. The nature of product technology development relies on obtaining information on the vehicle or system operation in carefully constructed environments and scenarios. With the exception of some limited destructive testing (such as crash testing), most product technology testing is non-destructive which allows a test vehicle to be used in a large number of experiments. Process technology development, on the other hand, relies on obtaining information about how a part, system or vehicle is built. Since each vehicle is built only once, there is no opportunity for a test vehicle to contribute significantly to further process development once it is built. Hence, for radically new processes it is unlikely significant learning of the new processes can occur in building only twenty to one hundred vehicles.

Insufficient process development can lead to problems during production and expensive downtime in a high-volume assembly plant. If new process technology cannot be fully developed using prototypes and pilot vehicles an intermediate step to develop the new process technology is required. Manufacturing a low-volume vehicle has a number of advantages when used as such a stepping stone. These benefits can be summarized as follows:

- Higher volumes than prototypes and test vehicles allow for more learning.
- Vehicles are built by production workers, providing a better simulation of actual high-volume manufacturing.
- Production problems causing downtime are not as costly as in high-volume assembly plants.
- Initial higher manufacturing costs due to new technology are not critical due to the lower price sensitivity of low-volume vehicles.
- Low-volume vehicles can be sold to collect revenue; pilot and prototype vehicles are typically destroyed after testing.

An excellent example of a high-volume automobile manufacturer producing and marketing a low-volume vehicle to aid in new process technology development is Audi's recently introduced A8 luxury sedan. The Audi A8 will be on sale in Europe in the summer of 1994 with production expected to fall between 15,000 and 20,000 per year. The Audi A8 is notable in that it uses an extruded aluminum space frame elements connected by cast aluminum "nodes" and covered by a skin of stamped aluminum sheet metal. This is radically different from the current methods of using stamped steel parts welded together to form the body structure of the automobile. As such, it requires completely new manufacturing and assembly processes to build. Not only has Audi had to invest time and effort in developing the design of the aluminum space frame concept, but has also had to explore how to mass manufacture a vehicle using such technology.

Yet the A8 is not so much a showcase for a different idea in body structure design, as a stepping stone on the way to high volume production of vehicles with such a body structure design. Audi and its partner, Alcoa, have invested over 10 years work and nearly $100 million into this effort with the intent of developing manufacturing techniques suitable for high-volume production in the near future. [Keebler, 1994]

The Audi A8 is not alone as being a low-volume vehicle which introduces new process technology. Several of the more notable low-volume vehicles have used radically new technology, as shown in the table below:

Vehicle	New Technologies Used
Acura NSX	Stamped aluminum body panels and structural parts; titanium connecting rods
Audi A8	Extruded and cast aluminum space frame
Dodge Viper	RTM body panels
Ford Ecostar	Sodium-sulphur battery
Jaguar XJ220	Aluminum honeycomb and high strength pressing structural components; adhesive bonding of components

Table 2.1 Low-Volume Vehicles Used to Develop New Technologies
[Source: Keebler, 1994]

While low-volume production may provide certain advantages in developing new technology, not all new technologies should be developed using low-volume production. The advantages of low-volume production in this area are best leveraged for technologies which require significantly new process technology for high-volume production. In this situation, low-volume production of a vehicle containing such a new technology is a logical intermediate step between small volume prototype and pilot production and high-volume production. Viewed in this manner, low-volume vehicle production can be thought of as an extended pilot run of saleable vehicles.

2.4 Using Low-Volume Vehicles to Satisfy Government Regulations

The fourth reason for high-volume automobile producers to investigate manufacturing low-volume vehicles is to satisfy future government regulations. One such regulation is the rapidly approaching California zero emission vehicle mandate. In response to declining air quality levels in the urban areas of California, the California Air Resources Board (CARB) issued a mandate requiring all automobile manufacturers with annual California sales in excess of 35,000 to offer zero-emission vehicles (ZEV's) for sale by the year 1998. This mandate states that in 1998 2.0% of such manufacturers sales must be ZEV's, increasing to 5.0% in 2001 and 10.0% in 2003. The following table provides estimates on the ZEV requirements of the seven largest selling producers based on 1992 California registrations:

Manufacturer	1998	2001	2003
General Motors	6,600	16,500	33,000
Ford	6,400	16,000	32,000
Toyota	3,900	9,750	19,500
Chrysler	2,700	6,750	13,500
Honda	2,500	6,250	12,500
Nissan	1,800	4,500	9,000
Mazda	900	2,250	4,500

Table 2.2 Future California ZEV Sales Requirements for Selected Manufacturers
[Source: Rechtin, 1993]

As one can see from this chart, all seven companies' required ZEV sales volume fall near or below the defining threshold volume of 30,000 meaning such vehicles could be classified as low-volume vehicles. These low volumes, by themselves, do not mean GM, Ford and the others are restricted to producing ZEV's at such volumes. Conceivably, the manufacturers could produce such vehicles in far higher volumes using current high-volume assembly techniques by simply building and selling more vehicles, both in California and in other markets. However, there are a number of reasons, relating to both the state of ZEV technology and estimates of potential ZEV market, that make this unlikely.

Currently, all designs of a zero-emissions vehicles replace the automobile's gasoline powered internal combustion engine with an electric powered motor running off a vehicle mounted energy storage system. However, much of the required technology to achieve an operable electric vehicle is in a nascent stage of development. Accordingly, electric vehicles (EV's) are currently very expensive and feature performance below that of gasoline powered vehicles. Until technical advances are made to both reduce EV technology costs and improve EV performance, it is quite conceivable the potential market for such vehicles will be small. As such, these seven high-volume manufacturers may be forced to sell low-volume EV's at a loss in order to meet the California mandate and be allowed to sell high-volume vehicles. Obviously, in this scenario any reduction in manufacturing costs on these vehicles can only improve the manufacturer's balance sheet. Such a reduction in costs can best be achieved by developing the ability to build low-volume vehicles in a cost efficient manner.

2.5 Summary

As one can see there are significant benefits available to manufacturers who produce an market low-volume vehicles alongside their current high-volume vehicles. The following matrix provides a summary of the likely reasons for the production of some low-volume vehicles. One should note this table is a representation of *likely* justifications for these vehicles; actual reasons would probably be confidential information within each manufacturer. Most of the vehicles listed are built by high-volume manufacturers. However, I have included two vehicles built by Jaguar, a low-volume producer, to show that even a low-volume manufacturer can reap the same benefits from a vehicle produced in much lower volumes than rest of their production models.

	Niche marketing	Brand image	Technology	Government regulations
Acura NSX	X	X	X	
Audi A8		X	X	
BMW 850i	X			
Buick Reatta	X	X		
Chrysler TEV (EV)			X	X
Dodge Viper		X	X	
Ford Ecostar (EV)			X	X
Jaguar XJ220	X	X	X	
Jaguar XJS-R	X	X		
Mercedes SL	X			

Table 2.3 Reasons for Producing Selected Low-Volume Vehicles

From this table it is clear there are a number of benefits most manufacturers hope to reap by producing low-volume vehicles. In the next section, however, I will show there are significant obstacles to many of these manufacturers from producing low-volume vehicles cost effectively. For reason which will be detailed in the next chapter, it is likely almost all low-volume vehicles have a higher per vehicle manufacturing cost than a comparable high-volume vehicle. Though section 2.1 showed vehicles marketed in market niches are able to command higher prices, there may not be sufficient price elasticity to increase the price until it covers all manufacturing costs. In such a case, the manufacturer might actually lose money on each low-volume vehicle it produces. However, all four of the benefits outlined in this chapter can be great enough for a manufacturer to justify losing some money on sales by making it up elsewhere.

3. Roadblocks to low volume vehicles

In the previous chapter I presented four reasons why it can be advantageous for a high-volume automobile manufacturer to produce a low-volume vehicle as a supplement to its high-volume business. The question then arises: why are not all high-volume manufacturers producing such vehicles?

The answer to this question can be found in the dynamics relating manufacturing costs and cycle time to the production volume of the vehicle. The dramatically lower production volumes of a low-volume vehicle require each vehicle to shoulder more of the burden of the investment and indirect costs involved in manufacturing. This can dramatically lower the contribution* of each vehicle and affect the profitability of producing such a vehicle. In addition, lower production volumes require dramatically longer cycle times. These longer time, in turn, can have a significant effect on the utilization of specialized equipment and the manner in which operators perform their work. Both of these factors can have a dramatic downward effect of the profitability of low-volume vehicles. These two effects of low-volume manufacturing will be explored in more detail in the following sections.

3.1 Effects of production volume on fixed cost allocation per vehicle

The key to understanding the effect of production volume on the per vehicle manufacturing cost lies in the allocation of initial investment costs and reoccurring indirect manufacturing costs to each vehicle produced and sold. Developing and building a modern automobile requires an enormous up front investment of capital. Depending on the extent of the vehicle program, this investment can range from hundreds of millions to several billion dollars for a single vehicle program. This investment reflects a number of costs including, but not limited to, the engineering time used in developing the vehicle and components, purchase of production machinery and tooling, and any required renovation and construction of production facilities. In addition, there are a number of costs incurred in manufacturing vehicles that cannot be attributed to any single vehicle. These include maintenance costs, utility costs, and supervision costs. Obviously, manufacturers would desire that the revenues from sales of the vehicles incurring these costs be sufficient

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* Contribution is defined as the amount each vehicle contributes to the company's profits. It is equal to the revenue derived from selling the vehicle minus the total costs that were incurred in producing that vehicle.

enough to pay off all costs over the lifetime of vehicle production . This would allow the manufacturer to gain a profit from its investment. Low production volumes make it more difficult to accomplish this.

A good way of demonstrating the effect of low production volumes on the allocation of investment and indirect costs is to perform a Cost-Volume-Profit (CVP) analysis. To begin this analysis, I will assume all costs associated with delivering a vehicle to the end buyer can be divided into three categories: initial investment, direct manufacturing costs and indirect manufacturing costs. These three costs are defined in the following manner:

Initial investment:	Costs incurred in developing the vehicle design and designing and building the manufacturing system. These costs are incurred prior to the commencement of vehicle production.
Direct manufacturing costs:	Costs incurred during the manufacture of a vehicle "that can be identified specifically with or traced to a given cost object (i.e. the vehicle) in an economically feasible way." [Horgren and Foster, 1991]
Indirect manufacturing costs:	Costs incurred during the manufacture of a vehicle "that cannot be identified specifically with or traced to a given cost object (i.e. the vehicle) in an economically feasible way."[Horgren and Foster, 1991]

In order to provide a better understanding of what costs are classified as either investment, direct or indirect costs, a breakdown of some significant manufacturing costs into these three categories is given in Table 3.1 below.

Investment Costs	Direct Costs	Indirect Costs
Engineering development	Wages of production operators	Wages of supervisors and managers
New production equipment	Material used in vehicles	Material handling
Facilities construction	Purchase cost of components	Vehicle transportation
Facilities renovation		Marketing
Prototype manufacturing		Facilities maintenance
Equipment upgrades		Equipment maintenance
		Utilities

Table 3.1 A Breakdown of Some Common Vehicle Manufacturing Costs

With such a cost structure definition, it is possible to calculate the contribution (C) each vehicle sold provides the company in the form of profits as follows:

$$C = \text{Revenue / car} - \text{Direct Costs} - \frac{\text{Investment} - \text{Annual Indirect costs} * \text{Lifespan}}{\text{Annual Production Volume}}$$

From this rather simple model it is clear the effect a lower production volume would have on the per vehicle contribution: it would drop significantly. This can be demonstrated in the following example. Two vehicles (A and B) with identical fixed and variable costs are produced in dramatically different volumes. Vehicle A is a high-volume vehicle and is built at a rate of 100,000 units per year over a four year lifetime. Vehicle B is a low-volume vehicle built at a rate of 25,000 units per year for over the same four year lifespan. For the purposes of this example I assume each vehicle is built in a separate but identical factory. I will examine the effects of this assumption later in this section. Table 3.2 demonstrates the effect this difference in production volume has on the contribution per vehicle when A and B are sold at the same price.

	Vehicle A	Vehicle B
Volume	100,000/yr.	25,000/yr.
Lifespan	4 years	4 years
Price	$ 20,000	$ 20,000
Total Fixed Costs		
Investment	$1 billion	$1 billion
Indirect costs	$ 0.5 B/yr.	$ 0.5 B/yr.
Cost Per Vehicle		
Investment	$ 2,500	$ 10,000
Indirect costs	$ 5,000	$ 20,000
Direct costs	$ 10,000	$ 10,000
Contribution/vehicle	+ $ 2,500	- $ 20,000

Table 3.2 A Cost Allocation Example

As shown, the contribution (i.e. profit) per vehicle for vehicle B is actually negative (-$20,000 per vehicle vs. +$2,500 per vehicle for A). This implies vehicle B is being sold at a loss to the company. Note that the direct costs for both vehicles remain identical when measured on a per vehicle basis, yet the indirect and investment costs per vehicle of B are four times the analogous costs of A,an amount equal to the ratio of their production volumes. This means that a manufacturer with expertise in producing vehicles profitably at volumes in excess of 100,000 units per year may not be able to achieve similar results at one-quarter of that volume.

However, it is important to note in this analysis I made one very important assumption: the indirect costs and initial investment are completely independent of production volume. In other words, I have assumed that the manufacturer of the two vehicles would use *exactly* the same methods, equipment, facilities and people in designing, developing and manufacturing the two vehicles. From this example one can see that high-volume development and production techniques used for low-volume vehicles result in a significant and undesirable increase in the per vehicle manufacturing costs. Thus, in order to to reap the benefits available from low-volume production explained in Chapter 2 without incurring huge losses per vehicle, it is necessary to do one or more of the following:

- Increase the revenue per vehicle by increasing the selling price of the vehicle
- Extend the lifespan of the vehicle to create a higher volume to allocate costs against
- Decrease the investment and indirect costs associated with low-volume vehicle production

The first two actions are used quite often by many low-volume manufacturers to improve the profitability of their vehicles. The Pepall's analysis of niche markets presented in section 2.1 demonstrated that it is possible to charge significantly higher prices for vehicles sold in niche markets (figure 2.7). In addition, the competitive advantage of a first mover in such a market could mean frequent model changes are unnecessary. Aston Martin, for example, sells vehicles that have been in production with relatively few changes for over several years at prices in excess of $200,000 per vehicle. These two actions work well in the markets Aston Martin and many other low-volume manufacturers compete in, namely ultra-luxury and ultra-high performance vehicles. The dynamics of these markets favor extended period of times between model changes as well as exorbitantly high prices. However, it is unlikely all niche markets would react as well to such extremes in vehicle prices and lifespans. As such, either increasing the selling price or extending the lifespan of the vehicle may not be acceptable actions for most high-volume manufacturers.

With this realization, there is only one remaining option: reduce the costs involved in developing and manufacturing low-volume vehicles. As the earlier examples showed, the most significant costs are the initial investment and indirect costs. This means manufacturers must examine each aspect of vehicle development and manufacturing to determine alternative methods that apply better to low-volume vehicle production. Table 3.3 gives a number of common methods of reducing these investment and indirect manufacturing costs. The methods are divided into two groups: those which deal with the development of the new vehicle design and those which deal with the manufacturing of the vehicle including the design and construction of the manufacturing system.

Vehicle Development	Vehicle Manufacturing
Use cross-functional, co-located teams Reduce the number of prototypes built Share capital intensive components with high-volume vehicles	Share production facilities with high-volume vehicles Share production equipment with high-volume vehicles Use equipment with low purchase and installation costs Use product flexible tools to allow tools to be used for several vehicles Use process flexible tools to allow fewer tools to do the same job

Table 3.3 Some Common Methods of Reducing Investment and Indirect Manufacturing Costs

As this table shows, there are a number of methods available to reduce the investment and indirect costs associated with automobile assembly. I will discuss some of these methods in further detail until explaining the effects longer cycle times can have on these same costs. This is done in the following section.

3.2 Effects of production volume on manufacturing cycle time

The previous section demonstrated that low-volume production can have a significant effect on the per vehicle manufacturing costs incurred in building such vehicles. This effect was due directly to the lower production volumes. The next three sections will demonstrate that low-volume production also has several indirect effects on these costs due to the increase in cycle times required for low-volume production.

Section 1.5 presented a summary of three common forms of low-volume automobile assembly. One feature common to two of these forms (craft production and production on a dedicated low-volume assembly line) is a significantly longer cycle time*. This larger cycle time is the lower total production volume of both manufacturing system

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* Cycle time is defined as the average time between the arrival of two consecutive products at a workstation.

compared to a high-volume system. Since total production volume for a blend-build system remains high there is little effect on cycle time.

The effect of total production volume on cycle time can be shown by the following formula relating the two quantities for the case of a single product, single shift assembly plant:

$$\text{Production volume} = \frac{\text{Hours per day} * \text{Production days/yr.}}{\text{cycle time}}$$

From this formula it is clear that in order to make low production volumes one must either reduce the time the assembly line is run (i.e. fewer production days per year or fewer hours per day or increase the cycle time. The first solution is not very feasible since it would mean a significant portion of the company's capital and labor would be idle and not contributing value to the company. This means the only feasible method of producing low-volume vehicles, other than blend-building, is to have long cycle times. The previously mentioned constraint on blend build production (i.e. require similarity in designs of derivative and base vehicles) means almost all production of unique low-volume vehicles is done in systems with long cycle times.

The extent to which cycle time is affected by lower production volumes can be seen in Figure 3.1. This figure plots the cycle time against production volume for a vehicle produced on a dedicated assembly line with one shift of laborers and no overtime.

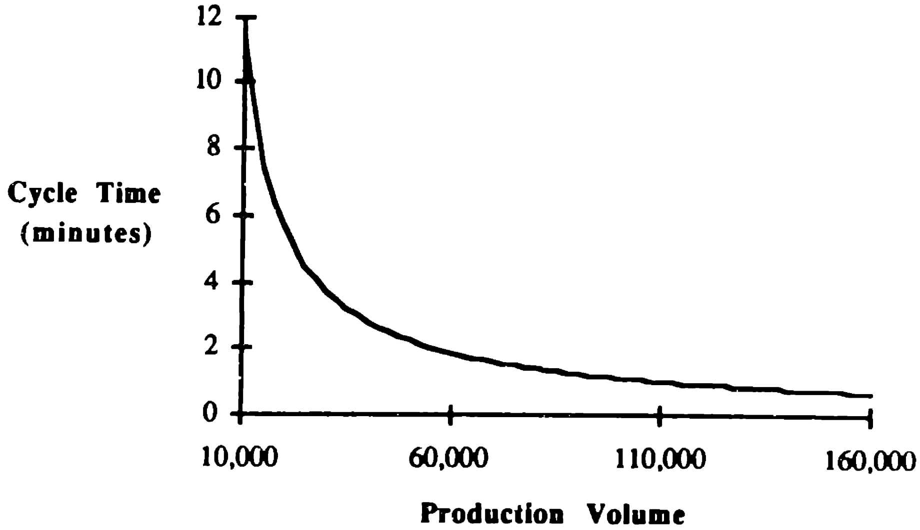

Figure 3.1 Cycle Time vs. Production Volume

As this graph demonstrates, the cycle time for low-volume vehicles (production volumes < 30,000 units) must be greater than 4 minutes, while for a typical high-volume vehicle this cycle time is closer to a minute. Also note there is a practical limit to the maximum production volume a single shift and assembly line can handle. This is why multiple plants, multiple shifts and overtime are all used extensively in building vehicles in volumes greater than 150,000 units.

This noticeable increase in the cycle time can have a number of effects on both the initial investment costs and indirect costs associated with manufacturing the vehicles. The two most significant of these effects are the lower utilization of specialized equipment and dramatically different assembly operator behavior, both of which can be traced to longer cycle times. The next section (section 3.3) will concentrate on the impact of cycle time on the utilization of equipment and its implications. Section 3.4 will discuss the effects on how assembly line operators perform their jobs.

3.3 Equipment utilization and specialization

The key to using equipment cost effectively in any form of production is to eliminate as much idle time of the equipment as feasible. Any idle time (i.e. time when the machines or tools are not being used) means the equipment is not contributing any value to the company. In accounting terms, the investment and indirect costs associated with the machine can be allocated over each use of the equipment. Fewer uses (i.e. more idle time) means the per use cost of the equipment is larger.Ideally, one would desire the equipment to be running continuously. Maintenance and line balancing concerns make this an unrealizable goal. Nevertheless, it is still desirable to minimize idle time (i.e. maximize utilization). Unfortunately, the longer cycle times of low-volume production make it more difficult to prevent this idle time.

For example, consider a windshield decking robot in a high-volume and low-volume situation. Assume that the windshield decking robot requires 50 seconds to load the windshield, apply the urethane adhesive and mount it to the vehicle. Using the same vehicle examples as before (A and B) we can see that the cycle times for each, based on previously quoted production volumes, would be 1.13 minutes and 4.51 minutes respectively[*]. In such a situation the relative utilizations and idle times of the robot are shown in the following table. As this example demonstrates, longer cycle times can lead directly to lower utilization rates and likewise higher idle times. This means the cost per use (and per vehicle) of the robot is much higher for vehicle B than vehicle A. I will show that this is most relevant to highly specialized equipment.

	Vehicle A	Vehicle B
Cycle time	67.8 s	271 s
Robot Working time	50 s	50 s
Avg. idle time	17.8 s	221 s
% utilization	73.7 %	18.5 %

Table 3.4 Effect of Cycle Time on Equipment Utilization (Windshield Decking Robot)

Modern high-volume automobile assembly typically uses equipment that is highly specialized in either the task it performs or the products it is capable of producing. In order to understand these different forms of specialization, I have developed two dimensions along which equipment specialization can be classified, product specialization and process specialization. These are defined as follows:

Product specialization:	The degree to which a tool or machine can be used for several vehicles. High product specialized equipment can be used in only a single vehicle, while low product specialized equipment can be used in several.
Process specialization::	The degree to which a tool or machine can be used for several independent (yet similar) operations on the same vehicle. High process specialized equipment can be used for only a single operation per vehicle, while low process specialized equipment can be used in several operations per vehicle..

Equipment can be classified by the degree of specialization along these two dimensions. A piece of equipment may be highly specialized along one dimension but less specialized in the other. Figure 3.2 provides a matrix with a breakdown of some common

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[*] Assuming 235 days of production, 8 hours per day.

automobile assembly equipment along these two dimensions. To provide a better understanding of these forms of specialization I will explore the specialization of two common forms of equipment: assembly robots and welding robots.

	Low Process Specialization	**High Process Specialization**
Low Product Specialization	Welding robots Transducer controlled nutrunners Assembly line workers	Pneumatic nutrunners Automated fluid fill machines Assembly robots
High Product Specialization	Fixed automation	Stamping dies Framing fixtures Multiple spindle nutrunners

Figure 3.2 Examples of Product and Process Specialized Equipment

Assembly robots have a high degree of process specialization and a low degree of product specialization. Most assembly robots are computer controlled, meaning they can be programmed to perform operations on different vehicle models. This feature afford assembly robots a low degree of product specialization. However, most of these robots are designed to only perform one operation per vehicle - for instance installing a windshield or placing a carpet in the vehicle. The vast difference between these assembly tasks makes it difficult to design a robot capable of performing both operations. For this reason, most assembly robots have a high degree of process specialization.

Welding robots, in contrast, have a high degree of both process and product specialization. The computer control of these robots provides them with product flexibility (i.e. low product specialization) in the same manner as assembly robots. However, these robots are also process flexible since they are used for several operations on a single vehicle. A welding robot might have ten or more spot welds to perform on each vehicle in a high-volume assembly line. Since there is little difference between each welds (other than location and possibly required current) the only constraints on how many welds a single robot can perform are time (i.e. how many welds are possible during the cycle time) and geometry (i.e. how many weld locations can the robot reach on the vehicle)

This distinction between product and process specialization is important since equipment with a high degree of process specialization is most affected by longer cycle times. Product specialized equipment, as I will later demonstrate, is less sensitive to the effects of longer cycle times.

The degree of process specialization is the key factor in determining the extent to which longer cycle times affect the utilization of the equipment. Equipment with a high degree of process specialization can be used on only a single operation on each vehicle. Whereas in a high-volume assembly plant this may not prove to be a problem, in low-volume production (with long cycle times) this necessarily leads to lower utilization rates. The choice of the windshield decking robot, a low product specialized and high process specialized piece of equipment, was very deliberate to prove just this point.

Equipment with a low degree of process specialization (also termed process flexible equipment), on the other hand, can be used for several operations on each vehicle. In high volume assembly this advantage is not exploited much since the short cycle times mean only a few operations are done to a vehicle at each workstation. However, in low-volume assembly the longer cycle times allow a single process flexible tool to perform several operations.

To illustrate this capability, consider the previous example. However, rather than a windshield decking robot, this time consider a process flexible tool such as a welding robot. The impact of the larger cycle time on the utilization of this equipment is summarized in Table 3.5 below.

	Vehicle A	Vehicle B
Cycle time	67.8 s	271 s
Avg. weld time	5 s	5 s
Welds / vehicle	10	40
Total time	50 s	200 s
Idle time	17.8 s	71 s
% utilization	73.7 %	73.8 %

Table 3.5 Effect of Cycle Time on Utilization

As shown, in the high volume case the welding robot is already being exploited for its process flexibility by performing 10 spot welds (i.e. 10 operations) during the cycle time. The longer cycle time for the low-volume case allows this flexibility to be exploited even more. In this case the weld robot is capable of performing 40 welds during a single cycle time period. This has two important effects. First, the utilization of the equipment stays high, reducing the indirect manufacturing costs. Second, and even more significantly, the number of weld robots needed for production decreases. In this example one robot in the low-volume case does the work of four robots in the high-volume case. This means three robots do not have to be purchased or installed - a definite savings in the initial investment cost for the vehicle.

In this manner the utilization of highly process specific equipment is very sensitive to longer cycle times. The degree of product specialization, on the other hand, is less significant to determining the effects of longer cycle times on equipment utilization. Extending the cycle time for a vehicle using both product specific and product flexible equipment will have the same effect on utilization for both types. However, this does not mean product specialization is not an important factor in the manufacturing cost of a vehicle.

Product specialization is very relevant in two aspects of automobile manufacturing costs: allocation of indirect costs in a multiple vehicle assembly line and allocation of the initial investment cost. Equipment with a high degree of product specialization used on a multiple product assembly line would require each product to have its own dedicated machine. This would result in both a low utilization and high initial investment costs.

Product specialization is also an important factor in the initial investment cost allocation for any vehicle assembly system. Investment costs incurred for equipment with a low degree of product specialization (i.e. product flexible equipment) can be allocated over a number of different vehicles built with the same machine. This can mean either multiple vehicles built simultaneously or future vehicles that can be built using the current equipment following the cancellation of current production. Investment costs for highly product specialized equipment, on the other hand, must be allocated to the single vehicle they are capable of producing.

3.4 Effects of Cycle Time on Assembly Line Operators

Longer cycle times can also have a significant effect on how assembly line operators perform their work. There are a number of aspects of assembly line work which rely on short cycle times for optimal worker performance. When the cycle time increases, these elements may make it more difficult for assembly line operators to perform their work effectively.

The effects of long cycle times are most pronounced in three areas: task learning by full-time operators, task learning by substitute operators, and worker pacing. The importance of these three aspects of assembly work and their impact on an operator's ability to perform his job are discussed below.

Task learning by full-time operators

The principle responsibility for an assembly line worker is to perform a certain set of assembly tasks on each vehicle passing through his workstation. In order to fulfill this responsibility successfully an operator must learn the tasks she is expected to perform. In automobile assembly, this means not only learning how to perform the tasks but also the correct sequence of tasks, what tools and parts to use, and which vehicles to perform which tasks on. This training process is termed task learning.

Task learning in a high-volume assembly plant is founded on the premise of learning through repetition of the tasks. It has been shown [reference? - Buzacott?] that the time an operator requires to perform his tasks diminishes with frequent repetition of the tasks. The mean time required to perform the tasks can be viewed as a measure of the operator's knowledge of the tasks. In this manner an operator learns from frequent repetition of identical (or similar) tasks.Research by Kilbridge (1962) suggests the optimal learning rate occurs for operations with cycle times near one minute As such, high-volume production systems typically feature rapid task learning rates due to the frequency of repetition and the relative simplicity (i.e. small number) of the tasks performed. Both of these factors are a direct result of the short cycle times inherent in such systems.

However, as I have shown in a previous section, lower production volumes necessarily result in longer cycle times. These longer cycle times have a significant impact on the learning rate of assembly operators for two reasons. First, a longer cycle time means a lower frequency of repetition of assembly tasks. Second, longer cycle times also mean more tasks per operator for each vehicle built. The combined effect of the lower repetition frequency and more complex set of operations is an increase in the difficulty of task learning for a typical assembly line worker. As tasks become more difficult to learn the probability of assembly errors increases. These assembly errors, such as forgetting to install a part or installing a part improperly, lead to costly repairs, lower throughput and lower product quality.

This problem is even more evident in assembly systems building multiple products as Morse [1992] states, "Imagine trying to assemble twenty different products every day. This would be difficult for anyone armed with quality assembly instructions, but consider the wasted time and material for someone without that tool or with solely verbal instructions. This is exactly what people in some of today's manufacturing facilities are faced with every day." In such a situation the tasks for each product may be similar yet still distinct. The result is higher complexity (more tasks to be learned) and an even lower repetition of each task. In this manner, multiple product production systems typically have lower learning rates than single product systems. When longer cycle times and multiple products are combined, the downward effect on learning rates is even greater. Thus, using current methods a multiple product, low-volume assembly system would have a much lower learning rate compared to a dedicated high-volume assembly line. This difficulty in task learning could result in off-line repair, lower product quality and lower throughput.

Task learning by substitute operators

Just as ordinary production operators must learn their assigned tasks, so must substitute operators who fill in for absent workers. Any production system using human workers must contain procedures to allow production to continue despite worker absences due to sickness, vacation, training or other reasons. Many high-volume assembly systems solve this problem by training some or all workers to perform the operations of several stations. In the event of a missing operator, one of these cross-trained substitutes is able to step in and perform the job with little disruption to the manufacturing system. The short cycle times of high-volume production make it easier for these substitutes to learn their tasks since each station contains only a handful of operations and the repetition rate is high.

As one might expect, dramatically lower production volumes affect substitute task learning in a manner similar to learning by full-time operators. With each station having more operations to be performed, training a person to know all the operations for several stations is inherently more difficult than in high-volume assembly lines. In addition, as each person in a low-volume production system is responsible for a greater percentage of the total work involved in vehicle production, the absence of any one worker is more critical in a low-volume system than in a high-volume system.

Thus, in the case of both full-time and substitute operator task learning, low-volume assembly systems require additional methods to overcome the shortcomings of repetitive learning methods in such systems. One such tool is Texas Instrument's Assembly Information system [Morse, 1992]. This system provides each operator with an assembly information booklet "that describes in detail how to build a product assuming that the reader has never seen the product of its component parts. Any assembler should be able to pick up an AI (Assembly Instruction booklet) and, based on the diagrams and descriptions, be able to assemble the product correctly with minimal assistance." With such an easy to access reference, operators are less likely to make assembly errors. Thus, these reference booklets can have a significant impact on product quality and cost. As I will show in part two of this thesis, the opportunity exists to use a similar system in low-volume automobile assembly.

Operator work pacing

As mentioned in section 1.5, one of the key attributes of most high-volume assembly systems is a fixed amount of time available for an operator to work on a vehicle. In attempting to perform his assigned tasks during the allotted time, an operator typically "paces" his work to ensure he finishes in time. If a worker paces himself too slowly, he may not complete all operations on all vehicles. Alternatively, an operator working more rapidly than necessary may yield a poor quality product. By rushing his or her work, an operator could fail to secure a fastener completely or forget to install a part.

In most high-volume assembly lines workers are able to pace themselves by the moving assembly line. Operators generally know how much time remains to work on the current vehicle by the location of the vehicle relative to a stationary reference point in their work area. In addition, the short cycle time of high-volume systems reduces the possible rest time between successive units that can be gained by working faster. Thus, there is less incentive in such systems for the workers to work (much) faster than the cycle time requires.

These high-volume solutions to worker pacing, however, are adversely affected by the increase in cycle times that accompany low-volume production. Longer cycle times mean there is more to be gained by working faster than necessary. In interviewing one worker about how he would deal with a ten minute cycle time, he responded that he would savor such a job as he would find a way to do the work in five minutes and have five minutes of his own time. As previously mentioned, this faster work pace could have an adverse effect on product quality.

In addition, the potential for workers to work too slow (inadvertently) is increased in low-volume production for two reasons. First, lower production volumes may mean a moving assembly line is either no longer feasible (due to initial investment costs) or moving at such a slow rate to make it difficult to discern its motion. Either case would make it more difficult for a worker to pace himself by this method. Second, the longer cycle time means a worker must pace himself over a longer time period. It is easy to imagine that a typical person might be better able to develop a consistent rhythm of activities spanning a minute and a half time period rather than over several minutes.

The purpose of this section was to provide the reader with an overview of some of the worker management issues that can arise from a switch to low-volume production. As described above, the longer cycle times of such a production system make it more difficult to solve these problems. However, these effects are difficult to quantify. In fact, it is possible the problems imposed by low volumes and long cycle times may not be as insurmountable as the previous discussion infers. Regardless, determining the extent of these effects was not a part of my research at Zeta Motor Company and, as such, will not be discussed in this thesis.

3.5 Summary

This chapter has shown that there are a number of obstacles which resist the efforts of high-volume manufacturers to build low-volume vehicles. These problems can be summarized as follows:

- Low-volume production causes the investment and indirect manufacturing costs per vehicle to increase dramatically, jeopardizing the profitability of building such vehicles.
- Low-volume production can cause low utilization for highly process specialized equipment.
- Low-volume production can have a significant impact on operator behavior issues such as worker and substitute task learning and worker pacing.

Any low-volume production system must address these problems to be fully successful. In part, this requires a re-examination of all the methods and tools involved in the development and manufacture of an automobile to find new methods more suitable for low-volume production. While this may appear to be a monolithic task, it is possible to provide a set of guidelines on ways to accomplish this task. In fact, I have already provided some examples of how to re-engineer automobile development and manufacturing to incorporate low-volume vehicles (see Table 3.3). These can be expanded into the following general guidelines on how to minimze investment and indirect costs for a dedicated low-volume production system:

- Use low cost alternatives to current high-volume equipment
- Use process and product flexible tooling.
- Share facilities (e.g. building space) with high-volume production system
- Share required process specialized tooling with high-volume vehicles

These guidelines can serve as a basis for evaluating how well a current manufacturing system or sub-system can deal with the burdens imposed by low-volume production. I will use these guidelines as a springboard for Part II of this thesis in which I will discuss my efforts at Zeta Motor Company to develop better methods for securing threaded fasteners in low-volume production.

4. Fastening Systems in Automobile Manufacturing

Part I of this thesis provided an overview of some of the benefits a low-volume vehicle can provide a high-volume vehicle manufacturer. In addition, it outlined some of the key impediments resisting the efforts of high-volume manufacturers to build such vehicles. These technical constraints have forced most high-volume automobile manufacturers to reconsider their methods of building vehicles in order to produce low-volume vehicles cost effectively. This re-evaluation of production methods must occur over the entire spectrum of operations which comprise modern automobile production.

In evaluating manufacturing methods for use in low-volume production it is necessary to investigate how low production volumes could affect each of these elements. From the discussion in the previous chapter, one can surmise the areas most influenced by changes in production volume are those which meet one or more of the following criteria: high initial investment costs, high indirect costs associated with poor utilization rates, and high degrees of both product and process specialization of equipment.

From these criteria, it is possible to identify several areas of vehicle assembly worthy of investigation. These include sheet metal stamping, in-plant vehicle conveyance systems (i.e. assembly line), vehicle framing fixtures, body shop welding, automated fluid-fill stations, and wheel alignment machinery. Most of these elements satisfy one or more of the criteria discussed above. However, these examples are limited in their scope compared to the entirely of vehicle assembly. This limited scope means intensive exploration of these areas may not provide huge benefits compared to the costs. In other words, they are weak leverage points.

However, there is one particular aspect of vehicle assembly which meets all of these criteria and is broad enough in scope to make it a strong leverage point for developing a low-volume manufacturing system. This leverage point is the systems and tools used for securing threaded fasteners in final assembly. My research at Zeta Motor Company concentrated on precisely this area of automobile assembly.

While at Zeta I evaluated current methods of securing threaded fasteners and developed specifications for a new fastening system for a future low-volume assembly line. The remainder of this thesis will document these efforts. Chapter 4 will provide a quick background of the importance of threaded fasteners in vehicle assembly and an evaluation of current fastening systems. The goal of this chapter is twofold. First, convince the reader that threaded fasteners are important to vehicle assembly; and second, demonstrate that current systems are inappropriate for low-volume production. Following this, Chapter 5 will highlight the development methodology used in creating a new low-volume fastening system, the Flexible Torque Nutrunner System. Next, Chapter 6 will provide a summary of the unique attributes of this system.Finally, both Chapters 6 and 7 will compare this new method of securing threaded fasteners to the existing methods presented in Chapter 4. This comparison will concentrate on the relative abilities of these systems to satisfy the special needs of low-volume production.

4.1 The Role of Threaded Fasteners in Automobile Assembly

The joining of two or more components is one of the most significant and widespread operation in automobile assembly. Once the body structure has been assembled, welded and painted, almost all remaining operations involve assembling components and attaching them to the vehicle. All of these operations, in turn, utilize some form of joining. Though there are a number of methods of joining parts, the majority of joining in the final assembly area uses threaded fasteners.

Methods of joining

There are essentially three different types of joining operations relevant to automobile assembly. These methods are characterized by the hardware used to hold the parts together in the following manner:

Threaded fastening	Joining two or more components using a third part, a threaded fastener, to provide the clamping and locating forces to hold the components together. Examples include: screws, bolts, nuts
Non-threaded mechanical joining:	Joining components using a non-threaded third part (i.e. the fastener) to provide the necessary clamping and locating forces. Examples include: rivets, dowel pins, clips

Non-mechanical joining:	Joining components without using a third part in the form of a fastener. Examples include: welding, adhesives

Due to the differences between these three methods of joining, each method has its own preferred applications. As we will see threaded fastening is both the most flexible and the most used of the three methods; non-mechanical joining, conversely, is the least used joining method.

Threaded fasteners are used in a wide variety of applications within an automobile. They are especially applicable in cases calling for easy disassembly for servicing or having large concentrated forces acting upon the fasteners. These two cases lead to threaded fasteners being used from the tiniest screw holding an interior trim plate in position to the much larger bolts which secure the engine to the body structure.

A growing number of joints use non-threaded fasteners due to the ease of assembly and possibilities for reduction in part count. However, non threaded mechanical fasteners are best suited for applications where expected forces on the fastener are low. Examples include wiring harness clips, and clips used to secure many interior and exterior trim pieces. Non-removable forms of non-threaded fasteners, rivets for instance, are not widely used in automobile final assembly due to the need for fastener removal and re-use during repairs.

Most of the remaining forms of joining parts (i.e. non-mechanical joining) typically produces a permanent joint between the two joined parts. Due to this permanency of its use, most of these forms of joining have few uses in the final assembly area of a modern automobile plant. These methods are used predominantly when the two parts: (1) face either low forces or forces spread over a large area, (2) do not have to be removed for typical repairs, (3) require a continuous bond between the parts for either vibration or sealing (i.e. prevent air/water leaks) reasons. This means non-mechanical joining is typically used in only four applications: windshield and fixed sideglass, sound absorber / headliner, and small ornamental trim such as interior and exterior badges.

Table 4.1 is designed to provide an understanding of both the usage of these three types of fastening and the preponderance of fastening operations in final assembly. This chart provides a breakdown of the major operations performed in the final assembly area and indicates which fastening method(s) may be used in each, if any. This chart demonstrates two important facts: the majority of operations (70 %) in the final assembly area of an automobile assembly plant involve fastening and almost as many operations (58%) use threaded fasteners as either the sole method or one of several methods of joining parts together.

Over the past several years there has been a trend away from using threaded fasteners in several scenarios. The ease of assembly of non-threaded fasteners and improving performance of non-mechanical fastening methods have lead to more designs replacing threaded fasteners with one of these two alternatives. However, these alternative joining methods have limitations in their ability to resist high forces and their ease of removal and re-assembly. These limitations ensure threaded fasteners will remain the most widely used method of fastening in the automobile industry for years to come.

	No fastening	Threaded	Non-threaded	Other
Trim				
Remove doors		x		
Install wiring harness		x	x	
Install air conditioning system		x		
Install sound absorber			x	x
Install fixed side glass		x		x
Install interior trim		x	x	
Assemble instrument panel		x	x	
Install instrument panel		x		
Install seat-belts		x		
Clean & frame glass	x			
Install foam tape	x			
Apply urethane sealant				x
Install windshield glass				x
Apply weather-stripping			x	
Install windshield wiper system		x	x	
Assemble seats		x	x	
Install seats		x		
Assemble doors		x	x	
Attach doors		x		
Set closure panel margins		x		
Test electrical system	x			
Chassis				
Dress engine		x		
Assemble front Suspension		x		
Assemble rear suspension		x		
Assemble tires and wheels				x
Build-up interior		x		
Build-up engine compartment		x	x	
Build-up underbody		x	x	
Locate and attach bumpers		x		
Install engine		x		
Install suspension		x		
Complete engine compartment		x	x	
Fill and test brake system	x			
Fill engine cooling system	x			
Fill power steering system	x			
Evacuate and fill A/C system	x			
Fill fuel tank	x			
Align wheels	x			
Roll (Dynamometer) test	x			
Test brakes	x			
Test engine control system	x			
Test anti-lock braking system	x			
Aim headlights		x		

Table 4.1 Forms of Joining in Automobile Final Assembly

4.2 Torque and threaded fasteners in automobile assembly

The purpose of a threaded fastener is to hold two or more components in definite position and orientation relative to each other. A threaded fastener achieves this purpose by generating a clamping force between the two components being joined. This clamping force is a compressive force which the fastener imparts to the two joined pieces, pressing them together and holding them stationary relative to each other. In using threaded fasteners it is necessary to ensure the threaded fastener provides the required clamping force between the joined parts under all circumstances. However, clamping force is difficult to measure in a non-destructive and cost effective manner. Instead, most manufacturers building products using threaded fasteners control the installation torque.

Torque can be thought of as a measure of the effort required to cause an object, such as a threaded fastener, to rotate. In securing a threaded fastener, a certain amount of torque is necessary to overcome the friction between the mated threads of the fastener. As the fastener is tightened, the torque required to turn the fastener increases. This is a result of an increase in the clamping force (brought about by the elastic deformation of the fastener and mating surfaces) which results in an increase in friction between the mated threads (higher contact forces). The higher the friction, the more effort required to rotate the fastener, the higher the torque associated with the fastener.

In this manner, one can see there is a direct proportionality between torque and clamping force. This allows torque, an easily measured quantity, to be used as a surrogate metric for clamping force. Common industry practice is to specify the clamping force desired on a particular fastener as a minimum peak installation torque. In other words, when installing any threaded fastener in a vehicle there is a minimum value of torque which must be achieved. Above this value of torque any additional rotation is unnecessary and possibly detrimental due to the potential for breaking either the joined parts or the fastener itself. On the other hand, a threaded fastener installed at too small of a torque may be susceptible to squeaking, rattling and loosening - all major quality and potential safety problems. Thus, the primary concern in assembling products with threaded fasteners is to ensure each fastener is tightened to its particular installation torque specification.

Table 4.1 demonstrated that threaded fasteners are used in an extremely wide variety of applications within a single vehicle. This wide range of usages means different loading situations and different joint geometries which in turn result in a wide variety of bolt sizes and required clamping forces. The combined effect of these factors is to yield a wide variety of required installation torques within a single vehicle. Figure 4.2 presents a histogram of the frequency of installation torques used in a typical vehicle built by Zeta Motor Company.

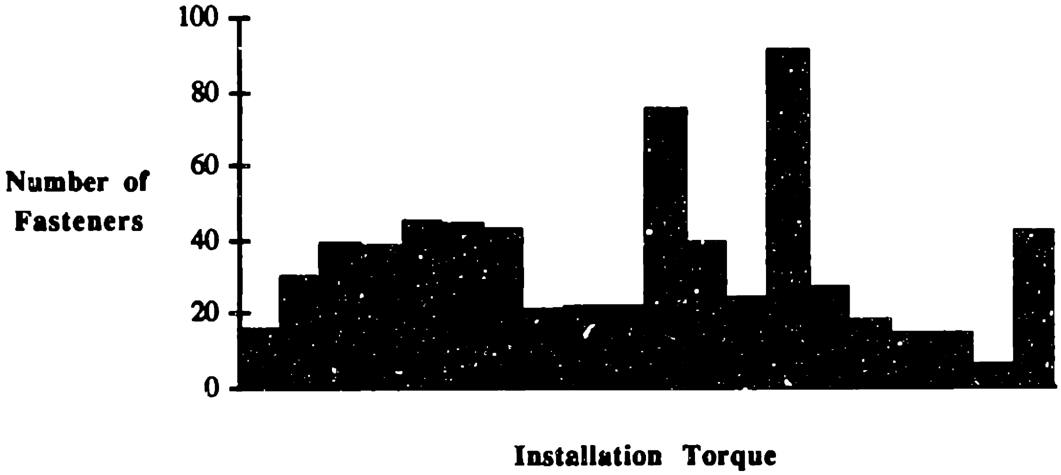

Figure 4.2 Histogram of Installation Torques for a Typical Vehicle

To finish this chapter, I will look at how threaded fasteners are secured during the assembly of a vehicle. Specifically, I will examine two areas: the tools used to secure the fasteners and the quality control methods used to monitor and control installation torque. In each area, I will explore methods currently in use in high-volume automobile assembly and investigate their ability to be used in low-volume vehicle assembly. By the end of this chapter it will be clear that these systems have serious limitations when faced with low production volumes. However, it will also be clear that certain systems may have advantages in low-volume production that are not being utilized in current high-volume applications.

4.3 Tools for securing threaded fasteners in automobile assembly

Threaded fasteners in an assembly plant are secured by means of a power tool known as a nutrunner. The nutrunner takes some form of energy (manual exertion, air pressure or electricity) and converts it to rotational energy to turn a threaded fastener. This rotation continues until a target torque is reached, at which time the tool stops rotating the fastener. A nutrunner can be classified by the following six attributes:

Power source:	The form of energy supplied to the tool which is subsequently converted to rotational energy. Power sources are typically pressurized air (pneumatic tools), electricity, or the operator himself.
Number of spindles:	The number of rotating output shafts. Multiple spindle tools allow several fasteners to be secured simultaneously or in a programmed sequence.
Mounting:	The manner in which tools are held. Tools can be either fixtured or hand-held. Hand-held tools can have a number of grip styles including pistol grip and right-angle nutrunners.
Trigger:	The manner in which the torque rundown cycle is triggered. This can be accomplished by either by a tool mounted switch or via an automated signal. Hand-held tools are exclusively hand-triggered.
Torque range:	The range of target torques a particular tool has been certified as being capable of producing. This range comes from direct testing of each tool's capability and reliability.
Torque control method:	The mechanism by which the tool stops rotating after achieving the target torque. The most common methods are pressure regulation (pneumatic tools only), mechanical clutch control and transducer feedback control.

The majority of nutrunners used in automobile assembly can be classified as hand-held, single spindle tools. Multiple spindle and fixtured tools are used in only a few limited applications. These tools are inherently low in product and process flexibility due to the geometric constraints of either the base fixture or the relative location of the individual spindles. In addition, such tools require significantly higher initial investment costs than hand-held nutrunners. As Chapter 3 demonstrated, manufacturing systems with high investment costs and low product and process flexibility are ill-suited for low-volume vehicle assembly. As such, these tools are inappropriate for low-volume production and will not be addressed in the remainder of this thesis.

With this restriction, there are currently four predominate tools used to secure threaded fasteners in automotive assembly. These tools can be classified as single-spindle, hand-held tools of one of the following configurations:

- Manual wrenches and screwdrivers
- Pneumatic, mechanically regulated nutrunners
- Electric powered, mechanical clutch controlled nutrunners
- Electric powered, transducer controlled nutrunners

These four types of tools are very distinct from one another and are described in more detail below.

Manual tools

Manual tools are those tools which require the operator to provide the energy to rotate the fastener. These include ordinary screwdrivers, nutdrivers, ratcheting socketwrenches, and torque wrenches. With the exception of torque wrenches, manual tools are incapable of providing any objective form of torque control other than operator experience. Torque wrenches, on the other hand, can provide two forms of torque control. In the first, the tool provides a visible readout of the current applied torque level which the operator uses to determine when to stop rotating. In the second method the tool provides a audible or tactile signal when the applied torque reaches a certain pre-set adjustable level. The most common of this form of tools is "click-stop" torque wrenches which provide an audible "click" when the set torque is achieved.

Manual tools have the advantage of being very flexible in the levels of torque provided and are capable of being adjusted with ease. However, there are a number of disadvantages to such tools. First, repetitive use of such tools can create significant ergonomic problems with the operators leading to medical problems such as carpal-tunnel syndrome. In addition, manual tools are remarkably slow in the time it takes to secure a fastener compared to motor driven tools. In the high-paced, short cycle time environment of a high-volume assembly plant this time loss is unallowable. As such, manual tools are typically used in only two areas of high-volume vehicle assembly: off-line repair stations and torque quality data collection (see section 4.4).

Pneumatic, mechanically-regulated tools

Pneumatic mechanically-regulated tools are the most common tools in automobile assembly. These tools use a supply of high-pressure (90 psi or more) air to spin a rotating vane motor which in turn causes the fastener to rotate. Torque is controlled by either a mechanical clutch or a pressure regulator. In the first method the clutch is adjusted so that it will slip at the target installation torque. The second method uses a pressure regulator to limit the air pressure supplied to the motor, thus resticting the torque output of the tool to the pre-set maximum. In either case it is important to note that such tools are capable of only one torque setting. If a different torque is required either the clutch or pressure regulator must be readjusted. Due to this, an assembly line work station must have one tool for each torque needed by the operator.

These tools have the advantage of being relatively lightweight and contain few complex parts (reducing costs). However, there are some disadvantages to such tools. First, most pneumatic tools require the air supply to contain oil to lubricate the tool motor. Unfortunately the oil is exhausted from the tool with the air during a rundown. This oily mist can result in both serious product quality problems (e.g. dirty or stained vehicles and parts) and safety concerns (e.g. slippery, oil-covered floors). Second, these tools are typically not as accurate as other nutrunners, especially transducer controlled electric nutrunners.

Electric-powered, clutch-controlled tools

These tools are nearly identical to pneumatic mechanical clutch controlled tools except they utilize electric motors rather than pneumatic motors. In fact some tool manufacturers offer electric tools which use the same parts as a pneumatic tool with the exception of the motor. The advantages of these tools over pneumatic mechanical-clutch controlled tools are threefold. First, electric motors are inherently more efficient than pneumatic motors. This means electric tool have much lower operating costs than pneumatic tools. Second, electric tools eliminate the oily exhaust from pneumatic tools resulting in a cleaner plant environment and cleaner products. Third, electric tools are often reversible allowing the same tool to be used to remove a threaded fastener in case of an assembly error or problem. Pneumatic tools, on the other hand, are rarely reversible.

Unfortunately, electric tools have some disadvantages compared to pneumatic tools. First, electric tools are typically more expensive than pneumatic tools of the same torque capability. Second, some electric tools have heat build-up problems in which near constant cycling of the motors, as encountered in a rapidly paced high-volume assembly line, causes the entire tool (including the handle) to get painfully hot. Third, electric tools have typically been heavier than pneumatic tools. These problems have limited the use of electric mechanical-clutch controlled tools in high-volume assembiy plants. However, the introduction of new cheaper, cooler-running, lightweight tools and the growing importance of product quality have led more of these tools to be used in automobile assembly plants.

Electric-powered, transducer controlled tools

Electric-powered, transducer-controlled tools use a significantly different torque control method than any of the previously discussed mechanical methods. These tools are equipped with an electronic transducer which measures the torque applied to the fastener and converts it into an electric signal. A separate controller containing a small computer regulates the current sent to the electric motor (and subsequently the torque of the tool) based on the transducer signal and a pre-programmed torque setting. In this manner, transducer controlled tools achieve a complete closed loop feedback control circuit, as opposed to the open-loop mechanical controllers of other tools.

This difference in control methods provides a number of advantages for electric-powered transducer-controlled tools. First, such nutrunners are generally more accurate. Second, the computer interface allows (in some systems) a number of torque settings to be programmed and selected between by a single switch. This allows a single tool to be used for multiple torque settings. Third, the abilities of the latest generation of controllers go beyond simple torque control. Present controller technology is such that tool speed can be varied during the rundown period to produce faster rundown without loss of accuracy.* Finally, the combination of the transducer and computer controller allows for easy torque data collection of all rundowns without any additional equipment.

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* There has traditionally been a tradeoff between the rotation speed and the accuracy of a nutrunner. High rotation speeds mean quicker rundown times but also more angular momentum, making it more difficult to stop rotation. However, by controlling the speed as a function of torque these tools are able to have high speeds during most of the rundown and shift to a lower speed as the torque approaches the target value.

However, these advantages do not come without a cost. The biggest disadvantage is precisely that, the cost. The additional equipment and increased complexity of these tools (particularly the transducer and controller) add significant costs to the system. In addition, these electric tools face the some of the same problems as mechanically-regulated electric tools, namely heat build-up and higher weight. These factors have prevented widescale use of transducer controlled electric tools in automobile assembly. The notable exception is in the assembly of engines where tighter tolerances require the improved accuracy these tools can offer.

The relative advantages and disadvantages of these four tool types can be best understood by examining their performance along four key manufacturing attributes: cost, time, quality and flexibility.[Chryssolouris, 1992] In order to provide an objective comparison of these four methods, I will define a number of objective metrics to measure these four key attributes. These metrics are as follows:

Cost: C1 = Initial investment (purchase & installation) cost

C2 = Average operating cost (per year per tool)

Time: T1 = Average time to secure bolt(a)

Quality: Q1 = Torque Capability (±3-sigma variation of torque as a % of target value)

Flexibility: F1 = Capable torque range(b)

F2 = Number of accessible torque settings per tool(c)

Using these metrics, the performance of the four tool types use in automobile assembly can be summarized in Table 4.2

(a) This time is based on an average of two typical bolts from results of an internal Zeta study on electric nutrunners. [Griffith, et. al. 1993]

(b) Capable torque range is defined as the number of Zeta Motor Company torque levels which a tool has been certified as capable of achieving with sufficient repeatability

(c) Number of accessible torque settings refers to the number torque values which the tool is capable of producing without resetting of the mechanical clutch or reprogramming of the transducer controller. Transducer controlled tools have the ability to change between a limited number of pre-programmed settings by rotating a selector switch.

	Cost		Time	Quality	Flexibility	
	C1	C2	T1	Q1	F1	F2
Manual tools	< $150	$0	>30 s	?	10	1
Pneumatic, clutch controlled	$1,650	$180	5.6 s	10 - 15%	1 - 3	1
Electric, clutch controlled	$6,000	$7	6.2 s	10 - 15%	1 - 3	1
Electric, transducer controlled	$11,500	$7	6.2 s	<10%	1 - 7	1 - 14

Table 4.2 Comparison of Four Common Nutrunner Tool Types

As one can see, there is no clear and away favorite among these tools. No single type of tool is capable of maximizing performance along all four of these attributes. For instance, manual tools are significantly cheaper than any of the powered alternatives. However, the much longer time to secure the fastener using these tools make them infeasible for even low-volume production. Thus, in selecting a tool system for a production line it is necessary to carefully weight the importance of each of these manufacturing elements and select the tools based on these weighted rankings.

Table 4.2 does not tell the entire story, though. This chart represents what the tools are capable of achieving. It does not reflect how the tools are actually used. For most of these tool types this distinction is insignificant. Manual, pneumatic and electric-powered clutch controlled tools are typically being used to the utmost of their abilities. The electric-powered transducer-controlled tools, on the other hand, are being significantly under utilized with respect to their capabilities. Current applications of electric powered, transducer-controlled nutrunners use them as direct substitutes for clutch controlled tools. In other words, they are constrained to producing a single torque per tool, nullifying one of the advantages of such tools - multiple available torque settings. The main reason for this is the way high-volume assembly lines are set-up. The short cycle times of a high-volume assembly line mean each station in the line on requires tools for a handful of operations. In this scenario it is possible to divide operations such that there are only one or two torques in a station eliminating the need for any flexible tools. However, as I will show in section 4.5, this need not be the case in low-volume automobile assembly.

4.4 Quality control methods for threaded fastener securing

Torque process control is a significant aspect of threaded fastening systems. The ideal goal of torque process control is to ensure all nutrunners are yielding the required installation torque at all times. As I will soon show, this may not always be possible.

Process control can be divided into three distinct functions: data collection, data analysis, and corrective actions. Data collection involves the measuring and recording of the key process parameters (such as torque) during or following actual operation. Data analysis uses statistical methods to discern trends and events from this raw collected data. Corrective actions involves a set of policies declaring what actions should be taken if the process is determined to be out of process control.

As one can see an important part of successful torque process control involves gathering accurate and relevant torque data. This data collection, in turn, depends heavily on the type of tools used, or more specifically, the form of torque control these tools utilize. Mechanically regulated tools (i.e. both clutch and pressure regulated tools) provide no method of measuring or recording the torque applied to a fastener. On the other hand, transducer controlled tools, by their very design, are continually monitoring the applied torque and can record such data rather easily. Thus, it should not be a surprise that the design of a torque process control system (and by inference its performance) hinges heavily on the tools used.

A summary of the torque process control system used at Zeta Motor Company's current assembly plants is provided in Appendix A. The important features to note are:

- Additional equipment and manpower is required for data collection
- The sampling rate is low for each joint* sampled (1 out of 20 at best)
- Only a few joints in the vehicle are sampled and analyzed
- Manual data entry and/or analysis may be necessary

It is important to realize these problems stem directly from the limitations of the torque control mechanism for the tools used in the plant. As previously mentioned, the majority of nutrunners used in automobile assembly are mechanically regulated. The torque

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* Joint refers to a fastener in any particular vehicle at a certain location. Fastener refers to a particular fastener in a particular vehicle.

process control system must accommodate for this fact by employing additional equipment to collect the torque data. The cost of this equipment and the limitations placed on data analysis by manual processing mean that only a very small number of fasteners can be measured and analyzed.

This has two important effects. First, for each joint measured the low sampling rate makes it more likely that defects (i.e. insufficient or excessive torque on a fastener) will be missed. This could lead to several vehicles being built with under-torqued or over-torqued fasteners before the problem is discovered, if it is discovered at all. Second, since the majority of joints are not measured at all, there is absolutely no effective manner of torque process control on these joints following the initial tool set-up. As such these joints might have consistent insufficient torque, yet there is no means of detecting this condition unless problems (e.g. squeaks, joint failures) occur later on.

Transducer controlled electric tools offer the potential for eradicating these limitations of the current process control system. The presence of a torque sensing transducer in such tools means every fastener rundown is being sampled as an integral part of the torquing process. Several new transducer controllers exploit this opportunity by incorporating automatic data collection and statistical process control (SPC) analysis in the controller itself. However, as previously mentioned, such systems have yet to be used in high-volume assembly plants to any great extent.

4.5 Effectiveness of current tool systems in low-volume production

Chapter 3 outlined some of the major problems which can occur when a high-volume manufacturing system or subsystem is used in low-volume production. In this discussion, I presented a number of attributes by which are relevant to the ability of such systems to operate at low-volumes. These include:

- Initial investment cost
- Indirect manufacturing costs
- Product flexibility of manufacturing equipment
- Process flexibility of manufacturing equipment

These attributes can be used to determine the effectiveness of current nutrunner systems in low-volume production. In addition, I have included two additional attributes, ease of data collection and ease of data analysis, to incorporate the influence of the tools on the process control system. Table 4.3 summarizes the results.

	Investment Cost	Indirect Cost	Product Flexibility	Process Flexibility	Ease of Data Collection	Ease of Data Analysis
Manual tools	Very low	Very low	Medium	Medium	Medium	Low
Pneumatic	Low	Medium	Medium	Medium	Low	Low
Electric mechanically controlled	Medium	Low	Medium	Medium	Low	Low
Electric transducer controlled	High	Low	High	High	High	High

Table 4.3 Comparison of Nutrunner Systems for Low-Volume Production

As one can see electric powered, transducer controlled nutrunners offer significant advantages over all other tools in all areas except for the investment costs. However, the possibilities for reducing the total number of nutrunners required by exploiting the high process flexibility of these tools may offset their high investment costs. For these reasons Zeta Motor Company decided to concentrate its efforts on developing a low-volume fastening system based on electric-powered, transducer controlled nutrunners. A summary of these efforts is provided in the following chapter.

5. Development of the Flexible Torque Nutrunner System

Chapter 4 demonstrated the importance of threaded fastener and nutrunner systems to the final assembly of an automobile. It also showed that current nutrunner systems, including both hardware and process control systems, are ill-suited for low-volume production. In addition, Chapter 3 presented a number of problems caused by low production volumes that can make the jobs of assembly line operators more difficult. Chief among these problems was the possibility of assembly workers, both regular workers and substitutes, forgetting their work assignments. This chapter will document the development of a combined low-volume production nutrunner and process information system, the Flexible Torque Nutrunner System, designed to alleviate these shortcomings of current systems.

The majority of this chapter will describe the methodology I used to develop this new system. In this discussion I will take care to balance the general description of these methods with details of the actual development as it occurred at Zeta. Following this description, the final section of this chapter (section 5.7) will provide a brief reflection on the merits and success of the development methods as they were actually employed.

5.1 Product Development Process Methodology - An Overview

In undertaking this development task, I decided to follow the product development model of Ulrich and Eppinger presented as part of the MIT course 15.793J, Product Development in the Manufacturing Firm. I chose this methodology based both on my familiarity with it and my belief that this methodology would be well suited for such a development project. The key elements of Ulrich and Eppinger's product development methodology can by summarized by Figure 5.1.

The development process is divided into nine distinct steps spanning from the very first product ideas to the manufacture of the actual product. These steps are followed in roughly sequential order, although there are some opportunities for iteration and parallel efforts as shown in the figure. For instance, identifying customer needs and concept generation can be worked on simultaneously The actions involved in each step are defined in the following manner:

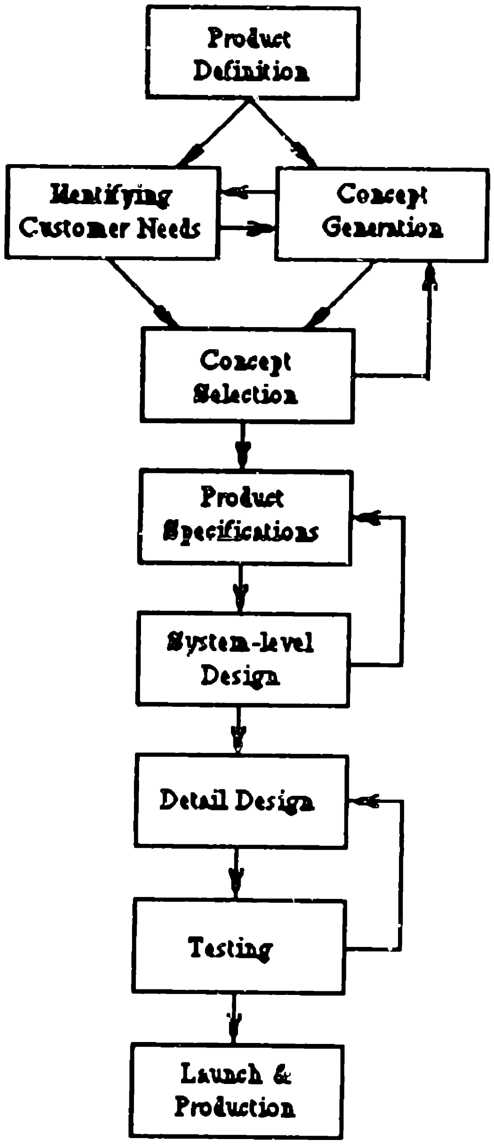

Figure 5.1 General Structure of Product Development Methodology
[Source: Ulrich and Eppinger, Class Notes, 1993]

Product definition:	The scope of the development project is defined and the objectives of the project are outlined in a mission statement.
Identifying customer needs:	The needs (i.e. requirements and preferences) of the customers and users of the proposed product are identified and ranked by the importance to the customer.
Concept generation:	Numerous concepts that may satisfy customer needs and the product definition are created. The emphasis in this step is generating a large number of concepts regardless of feasibility.
Concept selection:	The different concepts are evaluated relative to customer needs. From this evaluation, one or more concepts are selected for further investigation.
Product specifications:	The selected concepts are expanded into a more detailed form relating to the actual operating requirements or specifications of the product.
System-level design:	The product is analyzed and designed in terms of major functional systems and product architecture.
Detail design:	Individual components are designed.
Testing:	Prototype products are tested and evaluated.
Launch and production:	Final product design is manufactured and sold.

In developing a low-volume nutrunner and process information system at Zeta Motor Company, I used this methodology as the basic structure for my efforts. However, there were some factors which prevented the use of this methodology in its entirety. First, the short time period I was at Zeta (under seven months) did not provide me with enough time to complete the entire development process. As such, I only was able to complete the first five of these steps with the end result of my involvement being a set of written specifications for the proposed system. Since I was unable to complete the development process to fruition, I will present a brief summary of actions which still need to be completed by Zeta in a later part of this thesis (see Chapter 7).

A second factor which prevented wholesale adoption of this methodology involves assumptions made as part of this development model. This methodology was created for developing new products to be sold to consumers who are also the primary users of the product. However, the consumers (i.e. the people making the purchase decision) of the new nutrunner system at Zeta, the managers, were not the primary users of the system. While in most aspects of the development process this difference was inconsequential, there were a number of instances in which this difference required modification to the methodology. This thesis will show the effect of this difference was most pronounced during the identification of customer needs and the selection of product concepts. The modifications needed in these instances are highlighted in the discussion of process steps included in the following sections. These sections will detail the actual methods and tools used in the five steps of the development process accomplished during my tenure at Zeta Motor Company.

5.2 Product Definition

The primary purpose of the product definition step is to define the scope of the development project. The product definition, also known as a mission statement, should answer one of the following questions: what market are we trying to satisfy, or in the case of Zeta, what key functions are we seeking to provide? This definition should provide a description of the proposed product, as well as key assumptions on the product and its use. In addition, the product definition must be clear to all involved in the development process so it may serve as a common reference point in subsequent steps of the development process. In the development work at Zeta, this definition described both the key operating aspects of the nutrunner and process information system and similar details regarding Zeta's proposed low-volume assembly system.

The development of the low-volume nutrunner and process information system was part of a larger effort being undertaken at Zeta Motor Company. The purpose of this larger effort was to develop a low-volume automobile assembly system to provide Zeta with the ability to produce low-volume vehicles cost effectively. The proposed nutrunner and process information system was designed to operate as an integral component of this larger system. As such, the assumptions and goals of this assembly system were critical to the definitions of the nutrunner system. Thus, it is necessary to understand these global assumptions and goals prior to defining the scope of the nutrunner and process information system.

Zeta's Low-Volume Manufacturing System

In response to the benefits associated with low-volume vehicles and the problems with producing these vehicles using traditional high-volume manufacturing techniques, Zeta Motor Company embarked on the development of an assembly system better suited for low-volume vehicle production. This proposed assembly system, which I have termed the Low-Volume Manufacturing System (LVMS), represents a departure from traditional assembly lines in a number of aspects. The development of this system was concentrated exclusively on the final assembly area of automobile assembly. For this reason, the system assumes an input of welded and painted body structures, just as the final assembly area of a traditional plant would receive such inputs from the paint area. Other key characteristics of this system can be summarized as follows:

- Total line capacity of 2-10 jobs per hour (annual capacity 3,700 - 18,000 units)* depending on manpower allocation
- Constant cycle time of approximately 10-15 minutes
- Shared facilities with high-volume assembly plant
- Independent final assembly line
- Capability to manufacture several distinct vehicles simultaneously
- A moving assembly line capable of stopping individual vehicles for easier access during some assembly operations
- In-station repair of vehicle assembly errors and quality problems

These assumptions about the LVMS concept were very important to defining of the scope of the development project. In addition, these aspects of the global system design had significant effects in other areas of the development process. Examples of this influence will be presented throughout this chapter.

Initial Project Definitions

In the initial definition of the project scope, I defined three systems needed to support production as defined by the LVMS concept: electronic tool control, process reminding and worker pacing. Each of these systems provided a different function and, in the structure of the product development model, were viewed as independent "products".

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* Assumes 235 work days, single shift, 8 hour work day (no overtime).

Later in the development process, similarities between two of these systems allowed them to be combined into a single product. In this manner, electronic tool control and process reminding were merged to form the basis of the nutrunner - process information system which this part of my thesis concentrates on. At this point work on the worker pacing system was halted to devote more time to this combined system.

My first step in developing these systems was to write project definitions (or mission statements) for each of these systems. These mission statements included a brief definition of the system function as well as key assumptions and constraints. Figure 5.2 provides an abridged version of the definitions of both electronic tool control and process reminding.

Electronic Tool Control

Definition:

Computer based interface with electric transducer controlled nutrunners to perform the following functions:

- Select proper tool and torque parameters based on vehicle
- Collect and analyze data to automate nutrunner process control
- Check all nutrunner operations for acceptable readings (torque, angle?) before vehicle is advanced to next station
- Collect data for government mandated / safety related joints

Key Concerns / Requirements:

- Little or no interference with normal job routine
- Correct identification of current joint for parameter selection
- Operator locked out of tool and parameter definitions
- Capable of servicing several different vehicle models
- Allow for in-station repairs, including partial disassembly
- Segmentation of data by platform, station, tool, joint, fastener(?) for problem solving

Process Reminding System

Definition:

Computer based system to provide assembly line workers with a reminder of the correct sequence of operations for their station and access to more detailed information on how to perform individual tasks as needed.

Key Concerns / Requirements:

- Satisfies different needs of new / substitute / regular workers
- Support both assembly and disassembly of vehicles
- Allow for rapid changes in product design
- Interface styled to coach/remind worker rather than dictate/order
- Capable of servicing several different vehicle platforms simultaneously

Figure 5.2 System Product Definitions

As one can see, these first definitions assumed the use of electric-powered, transducer-controlled nutrunners and a rather elaborate computer interface to provide the process information. These assumptions were based on preliminary concepts made prior to my arrival at Zeta. At first I accepted these decisions and incorporated them into my assumptions. However, in developing concepts later on, these assumptions were too constraining. As such, I explored areas outside these narrow assumptions to provide some reasonable justification for making such assumptions. With each system so defined, the next step in the process outlined in Figure 5.1 was to identify the customer needs. This step is described in section 5.3 below.

5.3 Identifying Customer Needs

This part of the product development process is perhaps the most critical to the eventual success (or failure) of the process. It is during this step most of the interaction between the development team and the customers occurs. The nature of this interaction, in turn, directly influences the success or failure of the entire development project.

There are four key parts to this step of the development process. These are: defining the customers base, collecting the voice of the customer, generating a list of customer needs, and, finally, ranking these needs based on their importance to the customer. These four steps are explored in more detail in the pages that follow.

Defining the customer base

In most product development literature, the customer is inferred to be the individual responsible for both the initial purchase and the continued use of the product. However, in the case of the nutrunner-process information system, the concept of the "customer" was more ambiguous. Here the customer base was spread between three distinct groups: primary users, secondary users, and decision-makers. The first group, the primary users, included the assembly line workers who actually use such a system in production. The second group, secondary users, was comprised of people who would have only occasional (though important) interaction with the system. This included people involved in torque process control, people responsible for documenting product process information, and Zeta's internal computer systems personnel. The third group, termed decision-makers, included those people who would make the decision on implementing this system. This group included a number of managers and engineers working on the LVMS project and their supervisors.

Defining all three of these groups as customers was important to the success of the development project. Each of these groups had its own "stake" in the development of the system and the needs of each had to be addressed for the entire system to be successful. However, these groups did not form a homogeneous collection of customer needs. Instead, members of each of these groups had differing opinions on the requirements for a nutrunner-process information system. For this reason these groups were identified early in the development process. I will soon show that the differing opinions of these groups required some alterations to the generic product development methodology.

Collecting the voice of the customer

Collecting the voice of the customer involves interacting with customers to gather the information a development team requires to determine the "needs" of their customers. While there are a number of methods for achieving this, in my work at Zeta this was done primarily through interviews of the three groups of customers.

To collect the voice of the primary users, my supervisor and I interviewed twelve assembly line workers from a nearby Zeta Motor Company assembly plant . Each of these twelve participants were individually chosen by a former assistant plant manager (since transferred to the LVMS development team) based on their willingness to participate and their background. An effort was made to collect information from a diverse sampling of viewpoints. The actual interviews lasted approximately 45 minutes and were conducted in the assembly plant manager's office with the former assistant plant manager present. Both the location and the presence of the assistant plant manager were chosen to make the interviewees more comfortable, and hopefully to improve the effectiveness of the interviews.

The key goals of these interviews were to learn more about how assembly line workers perform their tasks, how they felt this might change with a significantly longer cycle time and how they work with computers. A list of questions asked in these interviews is included in Appendix B. These interviews were terminated after twelve people once the last few interviews failed to provide any significant additional information.

In addition to these interviews, I had a number of more informal meetings with the manager and some members of the LVMS development program, members of the Zeta Motor Company Fastening Systems Group and other Zeta personnel to collect the voice of the secondary users and decision-makers. The purpose of these meetings was twofold: to provide a benchmark of current systems used in high-volume assembly plants, and to determine what each group thought would be important to low-volume assembly plant. The specific topics of these meetings differed greatly depending on the area(s) of expertise of those involved.

Generating customer needs

The output of the previous step was several pages of interview and meeting notes. From these notes it was necessary to generate a list of customer needs that could be summarize the important points from these customer meetings and interviews. There were two methods of need generation used in this development project. The first involved translating needs directly from the text of the discussions and interviews. The second method involved creating an image KJ diagram* based on the discussions and then pairing elements of the interview text and this diagram to further expand the breadth of needs created. These two methods were so successful that I had to perform a "scrubbing" of these needs to reduce the number of needs to a more easily managed number. Each of these three steps is explained in the paragraphs below.

Due to the structure of the interviews and discussions in some cases it was possible to "translate" customer needs directly from what was said in the interviews. This involved taking a quote from an individual and reforming it such that it reflected a positive statement regarding a specific product requirement. In product development terminology this statement is known as a customer need. Examples of how some needs were translated directly from the voice of the customer are shown in Table 5.1.

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* A KJ diagram, also known as an affinity diagram, is a method of understanding relationships and causalities between diverse elements. A special form of KJ diagram, the image KJ, seeks to provide a deeper understanding of a set or actions (or use environment for a new product) based on images provided by participants in the actions. [Burchill 1991]

Voice of the Customer		Translated Need
"I don't have time to hunt and peck for keys"	⇒	The system requires a minimal amount of user input.
"I try to find the easiest way to do the job"	⇒	The system allows worker flexibility in the sequence of tasks performed.
"Should have examples of wrong placement or mistakes"	⇒	The worker knows if he has made an assembly mistake.

Table 5.1 Direct Translation of Customer Needs

The other method of generating customer needs involved creating an "image KJ diagram" and using the elements of this diagram to find unvoiced (or latent) needs in the dialogue of the customer interviews. This method was based on a procedures detailed by Burchill [1991] and Shiba [1990]. Once this KJ diagram was developed, additional customer needs were created by pairing images from the KJ with "voices" (i.e. quotes) taken from the interview dialogue and determining the key items shared between the image and the "voice". These key items were then used as the foundation for generating the need statements. The function of the KJ diagram in this use is to keep the needs relevant to the actual sentiments of the customer's statements as summarized in the image KJ. Table 5.2 presents some examples of needs generated in this manner.

Using this method allows multiple needs can often be triggered from the same voice by pairing it with another image from the KJ diagram. In this manner unexpressed or latent needs can be unearthed. An example of this is shown in table 5.2, in which two needs were generated from the same customer voice.

Customer Voice	Image	Key Items	Customer Need
"Rarely built vehicles would need some form of visual aids."	People don't always pay attention to what they are building.	"Rare", "paying attention"	The system ensures worker realizes requirements for vehicle being built.
"Rarely built vehicles would need some form of visual aids."	Workers try to figure out what next vehicle needs before it arrives.	"Rare", "pre-guessing"	The system provides information about next vehicle(s) before it arrives.
"A stationary car would be a problem."	I know I'm in trouble if my nutrunner cord runs out of slack	"Pace", "trouble"	The worker knows if he is falling off the pace.
"[Should] run the units in blocks of similar vehicles."	If a lot of cars are similar I don't look at the broadcast	"Similar", "ignore broadcast"	The worker is aware of differences between similar vehicles.

Table 5.2 Translation of Customer Needs Using an Image KJ

Due to the vast number of needs generated and the subtleties that separated different needs, it was necessary to create a method of referencing the origin of the need (i.e. the customer quote and image KJ element (if used)). This was done by assigning each need generated a numerical code. From this code it was possible to determine which interviewee triggered the need and the process used to generate the need. From this it was possible to clarify the meaning of the need when making decisions on including or eliminating the need by referencing the text of the interview itself.

The success of these two need generating methods was proven by the vast number of needs they generated. In fact, so many needs were generated that it was necessary to par them down to a more reasonable number. This was done by first organizing the needs into a number of different headings and sub-headings depending on the functional topic or area the need addressed. Once organized in this manner, I attempted to combine and eliminate those needs that expressed identical or very similar ideas. At the same time, I tried to be especially careful not to eliminate any needs that expressed a unique idea. This process was based on the multiple pick-up method proposed by Burchill [1991]. The entire process of refining the needs required several days to complete.

Ranking customer needs

Once I slimmed the number of customer needs down to a more manageable number, the next step involved assigning an importance or weight to each need. This weight reflects the relative importance of the needs to the customers. The key to this part of the process development process is to determine these relative rankings.

In my work at Zeta I attempted to measure the importance of needs through the use of surveys. Due to the broad diversity of the customer base I created four surveys to emphasize the different areas of expertise of different factions of the customer base. These four surveys included one on tools and torque process control, one on general and strategic issues, and two on topics relevant to assembly line workers. Two assembly worker surveys were created to reduce the number of questions to a more manageable number (on the order of 30 each) rather than create one large survey. This was done in the hope that a shorter survey would be more likely to be responded to. Unfortunately, at the time these surveys were completed, the high-volume plant the assembly line workers were employed at was in the midst of a new vehicle launch. The assembly worker surveys were thus never completed. The only survey to be completed was a more general (but also more comprehensive) survey of key people in the LVMS development team. The responses from these surveys were tabulated and averaged and the needs ranked by the average score (with secondary sorting by the highest single score given to the need). This ranked list of customer needs is included in Appendix C.

5.4 Concept Generation

This step of the product development methodology involves the creation of concepts of different product designs. The emphasis of this step is on exploring the complete boundaries of how the product requirements, as defined by the project definition and customer needs, can be fulfilled. Developing feasible concepts is not as important as developing a large number of diverse concepts. The reasoning behind this is similar to most brainstorming techniques - the best ideas may not be the first ideas but instead may be triggered by a totally implausible idea. In the development of the nutrunner-process information system three different tools were used to generate these concepts: functional diagrams, external searching (or benchmarking) and internal searching (brainstorming). These are discussed in more detail below.

Functional diagrams

A functional diagram provides a method of breaking a complex product or system into a number of smaller parts based on their function. A system divided into functional blocks can than be analyzed in a discrete manner such that concepts are generated for each functional block. This can be thought of as a "divide and conquer" scheme for creating product concepts. The key to this method is to divide the complete system into functional blocks of an appropriate level of abstraction. Dividing a system into too many or too few elements can lead to sub-optimal results. Figure 5.5 provides an example of a functional diagram of the electronic tool control system created during this step of the development process. Once such a diagram is created, concepts are generated for each functional block through one of the two methods discussed below.

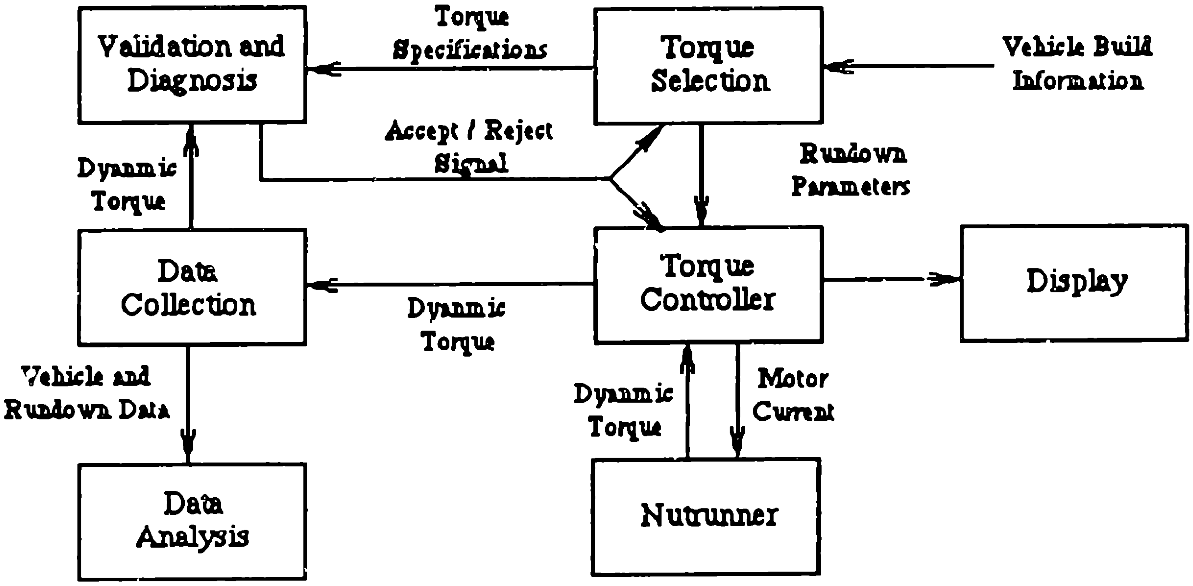

Figure 5.3 Functional Diagram of Electronic Tool Control

External Searching

External searching, or benchmarking, involves finding out how similar problems are addressed by other companies in the same and other industries. In developing the electric tool control and process reminding systems, this form of concept generation was done by a number of methods. These included discussions with representatives from nutrunner suppliers and Zeta's Fastening Systems group, and a literature search at a nearby university library. In addition, I was able to interview an individual who had recently joined Zeta from another automobile manufacturer (the Gamma Corporation). While at Gamma, this person had been involved with one of Gamma's low-volume vehicle production facilities. Her input was critical to understanding some of the problems that may arise from low-volume production and how Gamma dealt with some of these problems.

Internal Searching

Internal searching refers to the generation of concept ideas through methods more generally known as brainstorming. Drawing on the output of the other two concept generation tools (i.e. the functional diagrams and the knowledge gained by external searching), internal searching was used to create a large number of different concepts. This involved determining potential solutions to the problems of each sub-system identified in the functional diagrams. Many of these solutions (or concepts) were based on modifications of solutions found during external searching. Others were resulted from more outlandish ideas that came from brainstorming.

During this step in the development process I attempted to disregard any measures of feasibility in the concepts created. Instead, I sought to come up with as many ideas as possible. The end result of this step was a number of concepts and possible product attributes for each sub-system identified in the functional diagrams.

5.5 Concept Selection

Once I had developed a number of product concepts of varying degrees of feasibility, it became necessary to both "weed out" those concepts that are infeasible and highlight those concepts which best meet the needs of the customers. This is the goal of the concept selection step. By the end of this step, one should be left with either a single product concept or a small number of concepts for subsequent design and analysis.

The primary tool used in this step was a concept scoring matrix. This matrix provides a somewhat objective numerical scoring of the relative ability of each concept to satisfy customer needs. Each concept was scored on a 1 - 5 scale (5 being best) based on its ability to satisfy a particular customer need. Once such a matrix is formed, it is possible to determine an overall ranking of the concepts based on an average of the customer needs. An example of a concept scoring matrix used to evaluate different concepts for torque selection is shown in Appendix D.

However, in applying this method to the nutrunner system development, it became apparent the method was not able to discriminate between different concepts. As shown in the sample matrix of Appendix D, the averages of the concept scores were nearly indistinguishable from each other. Due to this indecisiveness, it was not possible to make conclusive decisions on the relative merits of any of the concepts.

In retrospect, the most important factor leading to this indecisiveness was the ambiguity of the customer needs and subsequent difficulties in ranking these needs. In re-examining the customer needs generated in this process, I discovered that many needs were ambiguous enough to make both the ranking of importance and scoring of product concepts difficult. For instance, two of the highest ranked needs were "the system ensures high quality vehicles are built" and "the employee feels the system is helping him." While I do not deny the importance of either of these needs, their broad meanings made it difficult to objectively rate how one concept would satisfy such a need relative to another concept. This can be seen in the similarity of the concept scores over a number of different customer needs.

For these reasons it became necessary to pass on a number of concepts for evaluation in later parts of the development process. Specifically this meant developing specifications for a number of concepts so each may be evaluated in a more objective (and hopefully more decisive) manner during the system-level design.

5.6 Developing Product Specifications

The primary goal of this step of the development process was to transform the broadly defined concepts selected in the previous step to a more detailed set of operating specifications. These specifications document the details of the selected product concept(s) in a manner which describes how the product is intended to operate. There are no well documented methods of transferring such concepts to more detailed specifications. For this reason, most of the efforts to create these detailed specifications were done in a relatively unstructured method. For the most part this involved explaining the product concepts in a detailed and informative manner. However, in writing these specifications I did create a number of flow charts to trace the system operation in some common operating scenarios. Due to the high degree of interaction between the operator and the system, I included both operator actions and system actions in these flowcharts. Appendix E contains final versions of these flowcharts.

These specifications were written in conjunction with personnel from Zeta's Fastening Systems Group. This partnership evolved midway through the development process when both groups realized the similarities of their two projects. The Fastening System Group was simultaneously investigating an electric-powered transducer-controlled nutrunner system for use in Zeta's pilot plant.* The Fastening Systems Group was developing a portable tool cart equipped with electric-powered transducer controlled nutrunners, interfaced to a personal computer. This tool cart would be capable of securing all threaded fasteners used in pilot production as well as providing easier collection of both dynamic and residual torque data. The similarities in the needs of the pilot plant and the Low Volume Manufacturing System led to the two groups collaborating in developing a new tool system. This collaboration will continue for the remainder of the system development with the pilot plant serving as a test for the future LVMS nutrunner and process information system.

5.7 Reflection on the development process

Looking back at the process used in the development of this nutrunner and process information system I feel it was generally successful. The system concepts derived from this process (see section 6.1 for details) are well suited to solving some of the problems associated with low-volume production. However, there were some areas in which this process, applied to this particular development project, fell short of expectations. The most notable of these problem areas were the previously mentioned difficulties with the customer needs surveys and concept scoring. Upon reflection there are a number of factors which may have contributed to these problems and should be addressed in any future development process.

The most influential of these factors was the assignment of personnel to the nutrunner and process information system development project. While there were a number of people assigned to different aspects of the Low Volume Manufacturing System development effort, I had almost sole responsibility for the nutrunner system development (prior to the collaboration with Fastening Systems). As such, most of the mechanics of the

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* The pilot plant is a central facility where Zeta Motor Company builds its pre-production pilots and some product prototypes prior to mass production at one of its high-volume assembly plants.

development process were done by a single person. This was especially critical in both the translation of customer needs and the generation of concepts. Not having help in these two particular steps greatly increased my workload as well as eliminating any input from another person. In retrospect, working on these steps alone was a mistake that should not be repeated.

Another factor which hindered the overall development of the project was the failure to receive feedback on customer needs in the form of the need surveys. By not eliciting feedback from both assembly line operators and tool specialists, a significant portion of the voice of the customer was ignored. This was likely a cause for the lack of decisiveness in the customer need weightings and the subsequent ineffectiveness of the concept scoring matrix.

Overall, however, the development methodology presented in the previous sections was well-suited to this project. The problems that arose during this development project were more problems of implementation than problems with the methodology itself. As such there is nor reason this development method cannot be used effectively for similar projects provided these implementation issues are addressed. The success of this method will be further highlighted in the following chapter in which the advantages of the newly developed tool system are demonstrated.

6. The Flexible Torque Nutrunner System

This penultimate chapter will discuss in detail the low-volume production nutrunner system developed at Zeta Motor Company. This system, which I have termed the Flexible Torque Nutrunner System (FTNS), was designed specifically to overcome some of the problems associated with low-volume automobile assembly. This chapter will detail how the Flexible Torque Nutrunner System solves these problems. It first provides a summary of the system hardware and the key features of this system and how these features distinguish it from current nutrunner systems. Following this, the remainder of this chapter and the next discuss the relative advantages these attributes provide the new system. This discussion will be in two parts. The first part will discuss the advantages and disadvantages of the new system in a general qualitative sense. The second part of this discussion, contained in Chapter 7, presents a more quantitative comparison, demonstrating how a traditional pneumatic nutrunner system and the Flexible Torque Nutrunner System would be used as part of Zeta's Low Volume Manufacturing System.

6.1 An Overview of System Hardware

There are three primary hardware components which make up the Flexible Torque Nutrunner System. These include the nutrunners, the controller and display unit, and the system computer. A general description of teach of these follows.

Nutrunners

The Flexible Torque Nutrunner System uses electric-powered, transducer-controlled nutrunners to perform the actual rundown of threaded fasteners. In addition to this function, these nutrunners also provide the controller dynamic torque data through an internal transducer. Each workstation in the LVMS has 2-3 nutrunners with different torque ranges such that together they cover the entire range of installation torques used in the station. The station also has a tray of sockets containing all the socket sizes and types (e.g. regular, deep-well, thin-wall, etc...) required for any vehicle to be built in the production system.

Controller and Display Unit

The second component of the Flexible Torque Nutrunner System is the controller and display unit. This unit is composed of the power and control circuitry of an electronic nutrunner controller connected to an alphanumerical / graphical display. This part of the system is responsible for the following functions:

- Controlling the dynamic torque and operation of the nutrunners (using a transducer feedback loop) to rundown parameters set by the system computer.
- Displaying process information for current vehicles
- Collecting and analyzing data of current rundown for acceptable final torque
- Display current torque data to aid in unsuccessful rundown diagnosis (when required)

Each workstation in the LVMS contains a single controller and display unit to control all nutrunners used in that station. However, if several operators are assigned to the same station, it may be necessary to provide additional displays and possibly controllers.

System Computer

The system computer is a personal computer that is either directly linked to a single controller unit (in which case the display is provided by the computer screen) or linked via a network to several controller-display units. The primary functions of the system computer includes:

- Setting the controller rundown parameters based on either input from the operator or automatically from a pre-programmed process sequence data file.
- Providing vehicle process data on current operation(s) for display at the controller
- Collecting peak torque data from controller for each rundown and segmenting the data in manner to facilitate easier analysis
- Providing data analysis tools or access to data through network links to allow analysis to be performed at a remote terminal

In addition, the system computer provides the capability of downloading data from two key Zeta information systems: Manufacturing Process Planning System (MPPS) and Order Control System (OCS). MPPS contains detailed process information listing each operation required to build any of the vehicles produced by Zeta. It is envisioned that the Flexible Torque Nutrunner System computer could receive process information directly from MPPS (likely through a one-time download) to eliminate re-entry of the same information into the system computer. OCS contains build information (e.g. exterior paint color, interior trim level, options included/deleted, etc..) for each vehicle in the production system. FTNS could link to OCS in real-time to provide broadcasting ability to the LVMS system.*

These links to MPPS and OCS are currently regarded as possible future features of the FTNS. The first versions of the FTNS, however, will be stand-alone systems (i.e. no direct link to outside computer systems). In this case, the functions of the system computer will be limited to the four primary functions presented above. The following section will discuss the major operational features these three component groups provide to the FTNS.

6.2 A Summary of Key Operational Features

While the hardware used by the FTNS is important, even more significant are the operational features these components provide. There are six such operational features which distinguish the Flexible Torque Nutrunnner System from existing nutrunner systems.Each of these features is discussed in detail below.

Multiple Torque Settings per Tool

One of the most unique aspects of this system is the large number of torque settings that can be served by a single nutrunner. As mentioned in Chapter 4, almost all current tool systems require one tool for each torque required in an assembly workstation. The use of electric-powered, transducer-controlled nutrunners allows a small number of tools (2 or 3) to cover a large range of installation torque settings. This provides the FTNS with a large

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* Broadcasting refers to the display of the OCS build data in a form which the operator can determine which parts and operations to perform on a per vehicle basis. Currently, most high-volume plants use coded printouts attached to the vehicle on the assembly line. Linking OCS to the FTNS would enable the display of vehicle specific process information (e.g. color of parts to use, additional operations required for an option contained on the vehicle, etc...).

degree of both product and process flexibility. As I will show below, this flexibility can be even further exploited by another feature of this nutrunner system, automated torque selection.

Automated Torque Selection

Automated torque selection programs the nutrunner controller with the rundown parameters automatically in preparation for the next fastener rundown with a minimum of input from the worker. At this stage of development there are two forms of automated torque selection still being considered. In the first form, the torque is selected and programmed into the controller based on which socket is attached to the nutrunner.* This is accomplished by incorporating a socket tray equipped with sensors to allow an interfaced computer/controller to determine which socket(s) is missing. Incorporating a subroutine to prevent the tool from being triggered in the event more than one socket is missing, makes it possible to determine which socket is on the tool and program the tool controller accordingly.

The second method of automated torque selection is more complex. In this method, an interfaced computer contains a pre-programmed sequence of torques. Upon receiving a successful rundown signal from the controller (i.e. the peak dynamic torque in excess of minimum installation torque) the computer advances to the next process step, down-loading the proper rundown parameters (target torque, rotational speed(s), speed shift point, etc...) to the tool controller. Compared to automated socket tray selection, this method has the advantage of allowing for custom tailoring of rundown parameters to specific joints. In addition the presence of such process information allows for better data collection by associating the measured data with a particular step in the assembly process. However, the potential for the worker to deviate from the programmed sequence means that the best form of torque selection would likely utilize both methods. In this combined form, the torque would be selected based on the programmed process sequence with the socket tray providing a double check. If the socket selected by the operator does not match the required socket for the joint (according to the programmed process plan) the tool is disabled and an error message is displayed, alerting the operator to the problem.

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* With few exceptions the installation torque of a fastener is the same for all fasteners with the same head diameter, as such it is possible to select the torque based on the socket being used. However, these few exceptions could prove to be complicating factors if this form of torque selection is implemented.

Dynamic torque data collection

Dynamic torque data collection uses one of the key features of transducer controlled nutrunners, their ease of torque data collection, to improve the process control of the nutrunner system. Due to the built in torque measuring transducer, it is possible to record dynamic torque data* for all rundowns. With the problem of data measurement so solved, the main concern becomes one of storing the data in a sensible manner to allow for easier data analysis.

Most current transducer controlled nutrunners with data collection store data in sequential form. This is acceptable when the tool is used for a small number of fasteners per vehicle. But in the case where the same tool will be used for a large number of fasteners at different torques, it becomes necessary to segment the data in a manner which will facilitate easier data analysis. By interfacing the controller to a computer or computer network it is possible to vastly improve this data segmentation. With the information provided by other parts of the system (e.g. process data from automated torque selection), it is possible to code the data to be analyzed in a number of ways. The data for each rundown (i.e. the peak dynamic torque) is stored along with the following information: time and date of rundown, process step, vehicle identification number (VIN), and a code discriminating between successful, unsuccessful and repair rundowns. With this added information the rundown data could be analyzed by all joints in a single vehicle, by a certain joint over several vehicles, or by repairs and unsuccessful rundowns for day's production, to name just a few possibilities.

Real-time rundown verification and diagnosis

The presence of a torque measuring transducer not only improves the ability to collect data on peak dynamic torque, but also allows one to analyze the dynamic torque during the entire rundown process. This ability can then be used to aid in the discovery and diagnosis of unsuccessful fastener rundowns. An unsuccessful fastener rundown occurs when the peak dynamic torque on the fastener lies outside the predetermined specification (or inspection) limits. These failed rundowns can be caused by a number of factors including: excessive variation in the nutrunner torque output, crossed or stripped threads, and differences in fastener lubrication.

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* See Appendix for distinction between dynamic and residual.

Normally the only method for detecting an unsuccessful rundown relies on the operator to observe a unusual torque reaction from the tool during rundown. The FTNS uses the dynamic torque data measured by the transducer to determine the peak dynamic torque for each rundown. This value can then be compared to preprogrammed torque specifications. In this manner each rundown can be verified that it is successful. If the rundown is unsuccessful, the same data can be used to diagnosis the problem.

Each of the previously mentioned failure modes has a unique relationship between torque and the angle of rotation of the fastener (i.e. number of revolutions of the fastener from inital thread engagement). A crossed thread, for example, would result in a large increase in the torque measured over a small rotation angle as the threads began to bind on each other. This behavior is readily apparent when torque is plotted against the angle of rotation. FTNS displays such a plot once a rundown is determined to be unsuccessful. The form of the curve (when viewed by a properly trained person) can aid in determining the possible failure mode of the rundown.

Process reminding

As mentioned in Chapter 3 there is a increased possibility of operator assembly error in long cycle time operations due to task learning difficulties. The process reminding feature of the system attempts to solve this problem by providing a display of process information relevant to the vehicle being built. The purpose of this information would be to remind the worker of what needs to be done on the vehicle. Depending on the configuration of the complete system, the possibility arises of tailoring the information displayed to the individual needs of each worker. For instance, additional information and/or diagrams could be provided in the case of a substitute worker.

This feature can be provided as an outgrowth of the pre-programmed process information required for process-based automated torque selection. A successful rundown would trigger the computer to change the process information and torque settings to that specified by a pre-programmed data file. However, there are a number of important aspects of process reminding which need to be better specified. These include exactly what information to display, how to display it and how to enter the information into the computer initially.

In-station vehicle repair capabilities

The reversibility of the nutrunners used by this system allows assembly problems to be repaired in-station by ordinary assembly workers rather than in a specialized off-line repair area. With an ordinary nutrunner system most assembly problems, such as a misinstalled part or a cross-threaded fastener, cannot be repaired in the station where the problem occurs since the tools are generally not capable of removing fasteners. Instead the vehicle continues to be assembled in the remaining stations of the assembly line and then proceeds to a repair area. Depending on the nature of the repair, large portions of the vehicle may need to be disassembled and reassembled to access and repair the problem. By providing the capability for in-station repair, most of this added work (and cost) can be eliminated since the problem can be addressed immediately upon discovery.

Eliminating such off-line repair areas also reduces the total number of tools and workers required for vehicle production. However, this feature makes it more difficult to provide other features of this system. In-station repair may require a worker to "back track" a few steps to repair a problem he found and then re-assemble everything. This means both automated torque selection and data collection routines must be capable of discerning the differences between normal rundowns and rundowns associated with repairs. If they are not capable of this, the system may select an improper torque setting or "tag" the torque data erroneously.

In order to understand the benefits of these attributes in a low-volume production situation it is necessary to compare this system to other currently used nutrunner systems. This comparison will be done in two parts. Section 6.3 will present a general description of several advantages the FTNS has over conventional nutrunner systems when used in low-volume production. Chapter 7 will present a more detailed quantitative comparison by examining how two nutrunner systems would be utilized as part of Zeta's Low Volume Manufacturing System.

6.3 A Qualitative Comparison of the Proposed System to Existing Systems

There are a number of advantages to the Flexible Torque Nutrunner System when used in a low-volume production system. However, there are also a few disadvantages compared to current systems. The most prominent and important advantages and disadvantages are discussed in detail below.

Improved product quality

One of the most important benefits of the Flexible Torque Nutrunner System is an increase in the quality of the vehicles being built. Product quality can be measured in a number of ways, and similarly there are a number of ways this nutrunner system improves quality. These include improved torque accuracy, fewer assembly errors and a cleaner (and safer) work environment. The factors which provide these benefits are discussed in more detail below.

The accuracy of a fastener's installation torque is very important to both the quality and safety of the finished vehicle. Fasteners installed to a torque lower than the specified target can rattle or squeak, leading to a poor perception of the vehicle's quality by the customer. Even worse, such a fastener might loosen itself to the point where it is no longer holding the parts together, impairing vehicle operation and jeopardizing the safety of the passengers. On the other hand, fasteners which are tightened to an installation torque higher than specified may lead to joint failure through damage to either the mated parts or the fastener itself (e.g. stripped threads). In such a situation the same safety and quality concerns arise as in the case of insufficient torque.

There are a number of ways the Flexible Torque Nutrunner System improves product quality by providing improved torque accuracy. The first is improved nutrunner capability through the use of transducer controlled nutrunners. As mentioned in Chapter 4, these tools have a better torque capability than mechanically controlled tools due to the closed loop feedback control circuitry. Compared to the open loop control of most other tools, transducer controlled tools have less variation of peak torque relative to the target torque. For instance the capability (Cp)[*] for many transducer controlled nutrunners is between 10% and 15%, while most mechanically controlled tools have a capability in the range of 15 - 25%. [From discussions with Zeta Fastening Systems experts] The lower Cp value for FTNS tools means the torque output is more likely to be close to the target torque. The effects of this difference in torque capability on quality is discussed in greater detail in Chapter 7.

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[*] Torque capability is defined as six times the standard deviation of the measured torque distribution of the tool as a percentage of the target torque. Lower values of torque capability mean there is less variation of the dynamic torque of the tool.

From this alone the Flexible Torque Nutrunner System is able to reduce the variation in the installation torque of threaded fasteners. However, there are two additional means by which the system provides improved torque accuracy. The first is real-time verification of each fastener rundown. As previously mentioned, real-time verification automatically compare the peak dynamic torque measured by the transducer to a pre-programmed torque specification. If the torque is below these specifica the worker is notified of the unacceptable rundown and prompted to retry the rundown. This ensures each fastener leaving the workstation is secured to acceptable final torque.

A third way the FTNS system can provide better torque accuracy is by improving the sampling coverage of torque data used for process control. As described in Chapter 4 and in Appendix A, the current torque process control system in place at Zeta relies on relatively infrequent measurements of residual torque. These measurements are performed on only the most critical joints; the majority of joints are not measured at all. With a transducer controlled nutrunner system, however, it is possible for the controller to sample dynamic torque data automatically from all rundowns and all joints.

There are two main benefits of this higher sampling coverage. First, the inclusion of all joints in the sampled data allows process control to be used on all joints, not just a handful. Subsequent data analysis could then pinpoint problem joints (e.g. joints with high rate of unacceptable rundowns), problem tools (e.g. tools with increasing torque output variance), and other quality threatening problems. Second, the more frequent sampling of each joint reduces the time it takes to determine the process is out of control (i.e. the average run length). This effect will be discussed in more detail in Chapter 7.

In addition to improved torque accuracy, the Flexible Torque Nutrunners System can improve the vehicle product quality by reducing the number of assembly errors. As mentioned in Chapter 3, the longer cycle times inherent in low-volume production make it more difficult for operators to learn their tasks. Operators who have not fully learned their tasks have the potential of making an assembly error including failing to install a required part, improperly installing a part, or installing the wrong part. All of these errors lead directly to a decline in product quality.

The process reminding system helps the worker learn his or her tasks and subsequently reduces the frequency of assembly errors. This aspect of the FTNS provides the operator with a summary of the tasks he or she is required to perform. With this information, the probability of an operator forgetting an assembly operation or performing a task out of sequence is reduced. The benefits of this feature are especially noticeable during the initial start-up period for a new model and whenever a substitute worker must replace a more experienced worker. Both of these scenarios typically create substantial decline in the quality of products due to learning difficulties the operators experience.

A third way the FTNS can improve product quality is by providing a cleaner and safer production environment. Using electric powered tools eliminates the oily mist exhausted from pneumatic tools. In most high-volume plants this oily exhaust condenses on nearby surfaces and either attract airborne dust particles (creating a covering of grime) or lubricates the exposed surface. As the closest surfaces to the tools are the floor around the assembly line and the vehicle itself, the potential quality and safety problems are readily apparent. In fact, this reason alone has led Zeta to adopt electric nutrunners in the seat assembly area for its luxury cars. The oily exhaust from the previous pneumatic tools had caused stains on the seat cover fabric. The use of electric tools subsequently eliminated this problem. In the same way the use of electric-powered tools in the FTNS addresses these concerns

Fewer tools required for production

Another benefit of the Flexible Torque Nutrunner System is the dramatically lower number of tools required for production. The high degree of flexibility of electric transducer-controlled nutrunners allows a single tool to be used for a number of fasteners with different torque specifications. This means each station in the Low Volume Manufacturing System would require only 2 or 3 nutrunners to cover the entire range of fastener torques needed. A traditional nutrunner system, on the other hand, would require a single tool for each unique torque setting for a fastener assembled in the station. In addition, the in-station repair FTNS allows, eliminates need for even more tools located in off-line repair areas. Finally, the fewer tools in use in the complete production system would mean fewer tools would be required to be held in reserve in the event of tool failure during production.

In addition to a lower quantity of nutrunners required in the entire manufacturing system, the Flexible Torque Nutrunner System requires fewer models of nutrunners. Since many electric tools are capable of larger torque ranges than pneumatic tools, only four tool models would be required for the entire Flexible Torque Nutrunner System (see Figure

7.1). If a pneumatic system were used a different tool model would be required for nearly every torque setting. For instance, a pneumatic tool capable of 10 Nm would not be capable of 20 Nm with the required repeatability. For this reason a manufacturing system using pneumatic tools would require twenty or more tool models throughout the system.

The principal benefit of fewer tools, both in quantity and number of different nutrunner models, is a reduction in the investment, operating and indirect costs associated with the nutrunner system. Obviously, a smaller quantity of tools translates into less tools which have to be purchased prior to production, thus reducing investment costs. In addition, these tools would have a higher utilization rate than tools assigned to a fixed torque setting. Since each individual tool performs more rundowns per vehicle, it has less idle time. As chapter 3 showed, reducing idle time reduces indirect costs. Furthermore, the benefits of having a small number of different tool types would be reflected in the indirect manufacturing costs associated with tool maintenance. Not only are fewer tools and replacement parts required, but the training costs associated with teaching the maintenance personnel how to fix the tools would be lower, since fewer tools would need to be learned.

Improved ability to build multiple vehicles on same assembly line

A third major benefit of the Flexible Torque Nutrunner System is an improved ability to build multiple vehicles on the same assembly line. In other words, FTNS expands the product flexibility of the complete LVMS system. Chapter 3 showed the benefits of using product flexible tools to defray the investment and indirect costs over a larger number of vehicles, reducing the per vehicle costs. The same is true for an entire manufacturing system with high product flexibility.

The Flexible Torque Nutrunner System expands the product flexibility of the LVMS in two ways. First, the flexible nature of the tools (both product-wise and process-wise) eliminate constraints present in manufacturing systems using fixed torque nutrunners. Fixed torque nutrunner systems, as previously mentioned, require a different tool for each torque setting required in a station. This means that, depending on the allocation of tools, some operations cannot be performed in some stations. Thus, to build a second (or third, or fourth) vehicle on the same assembly line, some workstations would require either even more tools or complicated reallocation of operations to other stations with the proper tools. However, using the Flexible Torque Nutrunner System this constraint is virtually eliminated, as will be shown in Chapter 7.

The second means by which the FTNS improves the overall product flexibility of the manufacturing system is through the process reminding system. As discussed in Chapter 3, one of the biggest problems with building a mix of products on the same assembly line is the potential for assembly errors by an operator. Most of these problems can be traced to the difficulty in operator task learning for multiple products. Earlier in this section I explained that process reminding reduces the probability of such errors in single vehicle production by reminding the worker of what needs to be done. This feature is even more useful when multiple vehicles are built on the same line by the same workers.

Despite these important advantages the Flexible Torque Nutrunner System demonstrates over current fixed torque systems, there are a number of disadvantages associated with this newly developed system. However, I will show that some of these disadvantages can be overcome if properly addressed. They are discussed in more detail below.

Higher System Complexity

One of the disadvantages of the Flexible Torque Nutrunner System is its higher complexity compared to current fixed torque systems. This new system relies heavily on relatively complex electronic hardware in all aspects of its operation. The use of automated torque selection and other system-wide functions means a problem in one part of the FTNS system could lead to the entire system going down. If this were to happen the entire manufacturing system would be disabled. On the other hand, in most pneumatic systems the majority of hardware problems can be traced to either the tool or the hose supplying air to the tool. In either case, the damaged part is either quickly repaired or replaced by a spare, with little impact on the remainder of the system. Thus extra effort must be expended during the design of this system to insure the additional complexity does not result in high downtime.

Another effect of the complexity of the FTNS system is the reliance on very specific hardware. Unlike pneumatic nutrunners which just need to be plugged into an air hose, electric transducer-controlled tools can only be used with controllers from the same manufacturers. Each manufacturer has its own distinctive wiring circuitry and connector design. By choosing a certain tool manufacturer to provide the initial system, Zeta is essentially locking itself into that one supplier. If another tool supplier develops a significantly better tool or controller system, Zeta could not use that system unless it were to scrap the current tools and controllers, or redevelop the system to allow the new controllers and tools to operate side by side with the initial tools. In an attempt to minimize this the written specifications required the tool system to be capable of operating nutrunners from different suppliers. Whether this is technically feasible, or strategically feasible on the part of the system and tool supplier, remains to be seen.

Higher Investment Costs

By far the most significant detriment of the Flexible Torque Nutrunner System is the high investment cost of the system. This higher investment cost is derived from a number of factors. To begin with, the system has high hardware costs. Even though fewer total tools are required in the Flexible Torque Nutrunner System, the electric transducer controlled tools cost more on a per tool basis. In addition, each tool requires a controller costing several thousands of dollars, though a single controller can be used for a small number of tools. The system computer and network links mean even more hardware costs for the system. In addition to these hardware costs, there are a number of other investment costs associated with the system. Chief among these is the cost of developing the system and the system software.

Chapter 3 showed that such high investment costs can be especially harmful for a low-volume vehicle. Due to the lower volume of vehicles these investment costs can be spread over, the per vehicle investment cost can grow to the point that the vehicle costs more to make than it can be sold for. Looked at in this light, the Flexible Torque Nutrunner System may seem too expensive for use in a low-volume production system. However, the Flexible Torque Nutrunner System is able to mitigate this through its high product flexibility and the high product flexibility it provides the entire production system. By building more vehicles using the same equipment the cost of the Flexible Torque Nutrunner System can then be spread over a larger number of vehicles. This is demonstrated in Chapter 7.

In addition, the collaboration with Zeta's Fastening Systems Group during the development of this system has provided the system with an additional form of flexibility - flexibility of use. The system can operate in two distinct uses: building and recording data on pre-production vehicles in the the pilot plant and building low-volume production vehicles in the LVMS. This means the initial development costs can be partly paid for by the pilot plant (and in turn by higher volume vehicle sales) again reducing in per vehicle investment cost and improving the profitability of low-volume vehicles using such a system. While this spreading of the investment costs may not reduce the per vehicle investment costs to the low levels of a fixed torque pneumatic nutrunner system, it should reduce costs to the point where the previously discussed advantages makes the additional cost worthwhile.

Reduction of Worker Independence

A final detriment of the Flexible Torque Nutrunner System is its reduction in the worker's perceived (and actual) independence. During the development of the new system, interviews with assembly line workers indicated that many change the sequence of operations they perform to find the easiest method of performing their tasks. In traditional production systems this is not a problem, but the fixed sequence of the automatic torque selection and process reminding eliminate this freedom. This could result in low worker morale (from the perception of being "forced" to do things in a certain way) and possible quality problems if the worker deviates from the programmed sequence (for instance a fastener may be secured to the improper torque). To prevent these two problems it might be necessary to either incorporate greater worker input into the initial sequencing of tasks or allow the operator to change the programmed sequence.

6.4 Summary

This chapter presented a summary of the key components and operational features which comprise the Flexible Torque Nutrunner System. These features provide the FTNS with several important advantages over traditional nutrunner systems applied to a low-volume production system including: better product quality, lower indirect costs through fewer tools, and lower per vehicle investment costs through higher product flexibility. However, the FTNS does have some significant disadvantages as a low-volume nutrunner system when compared to more traditional nutrunner systems. These disadvantages include: higher system complexity, higher total investment costs and a reduction in the freedom of the assembly line operator.

The key to judging the merits of the FTNS as a low-volume production nutrunner system lies in the interactions of these, and other, advantages and disadvantages. To provide a better understand of these interactions, and thus the merits of FTNS in general, the following chapter presents a more quantitative comparison of the FTNS and a traditional pneumatic nutrunner system.

7. A Quantitative Comparison of Two Nutrunner Systems

The previous chapter presented a qualitative comparison of the FTNS and traditional nutrunner systems To provide an even better understanding of the relative advantages and disadvantages of each system, this chapter presents a quantitative comparison of two systems: the FTNS and a traditional pneumatic nutrunner system. These comparisons will emphasize the differences between the systems along the same four key dimensions presented in Chapter 4: cost, quality, flexibility and time. This chapter also addresses the effects of different cycle times and multiple products on these systems. These comparisons will be made by exploring how the Flexible Torque Nutrunner System and a traditional nutrunner system would be used in workstations as part of Zeta's proposed Low Volume Manufacturing System.

Two Sample Workstations

The basis for most of the following quantitative comparisons is the differences between the two systems when applied to a workstation of the Low Volume Manufacturing System. I have created two sample LVMS workstations, Station A and Station B to reflect typical task allocations for a workstation within the LVMS. The composition and performance of the two nutrunner systems applied to these two stations provides the structure for the comparisons in this chapter. Using these two stations in this manner allows comparisons to be made on actual tools rather than on generalizations on the two systems, as in the previous chapter.

The individual steps and torque requirements of both of these stations were taken directly from the process sheets* of a proposed low-volume Zeta vehicle. These steps, which would be spread amongst several stations in a high-volume system, were collected to form the two stations, each containing approximately 15 minutes of work. This cycle time (i.e. 15 minutes) is the projected cycle time for the LVMS and corresponds to an annual production volume of 7,520 units.

These two workstations represent two dramatically different station possibilities. The key characteristics differentiating these two stations are presented in Table 7.1. Station

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* Each vehicle built by Zeta has a computerized set of process sheets (contained in MPPS) which list all the operations involved in building that vehicle model, the tools required and the standard times to complete each step. A summary of the operations contained in each station is included in Appendix G.

A involves the installation of the front suspension on to the vehicle. This station contains a large number of threaded fastener operations with several different torque requirements for these fasteners. In addition, station A contains a large number of mandatory compliance joints.* Station B, alternatively, is the site for the assembly and installation of the instrument panel. This station contains a larger number of non-threaded fastener operations and fewer unique torque requirements. The torque values within this station are significantly smaller than in Station A, and there are no mandatory compliance joints.

	Station A	Station B
Description of operations	Front suspension installation	Instrument panel assembly and installation
Total operation time:	14.09 min	13.53 min
Number of operations:	12	36
Number of threaded fastening operations:	8	9
Number of threaded fasteners·	38	31
Number of non-threaded fastening operations:	0	25
Number of mandatory compliance operations:	8	0
Number of different torque values:	7	4
Range of torque specifications:	15 - 90 Nm	1 - 4 Nm

Table 7.1 Summary of Simulated Workstations

Designing these stations to reflect these two distinct scenarios of final assembly, yet still realistically portray a typical station in the proposed LVMS, makes it possible to compare the overall performance of a fixed torque pneumatic tool system and the Flexible

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* Mandatory compliance joints are joints in which a failure can lead to serious quality, operation and/or safety concerns. Under the current torque process control strategy, the residual torque of these fasteners must be measured ten times per shift.

Torque Nutrunner System in a number of different scenarios. These comparisons are contained in the following four sections grouped by the four previously mentioned attributes starting with flexibility.

7.1 Flexibility

The discussion in the previous chapter concluded the product and process flexibility of the FTNS results in fewer tools, fewer tool models and improved product flexibility of the entire LVMS. Table 7.2 quantifies these effects by comparing the pneumatic and Flexible Torque Nutrunner systems over three metrics of flexibility. This data reflects the flexibility of the tool systems applied to Station A. The first two metrics, number of tools and number of tool models, are measures of process flexibility, while the third metric, number of available torque settings, is a measure of product flexibility.

Process Flexibility

As shown in the table the quantity of nutrunners required within the workstation to perform the required rundowns is lower for the FTNS than the pneumatic nutrunner system. Only two nutrunners are required by the FTNS compared to seven pneumatic nutrunners. Similarly, fewer distinct nutrunner models are required by the FTNS. However, this difference (two vs. four) was less pronounced than the difference in the number of tools. In equipping a station some identical tools (i.e. same tool model) may be used for different torques if the tool's torque range allows. For instance, for Station A one pneumatic tool model (designated Pneumatic 3) is used for three different torques. However, since this is a fixed torque tool, three identical tools, each set to a different torque, are required.

	Pneumatic	FTNS
Number of tools	7	2
Number of tool models	4	2
Available torque settings	7	11

Table 7.2 Flexibility of Nutrunner Systems for Station A

The two factors which allows the FTNS to require fewer tools and tool models are the multiple accessible torque settings and larger capable torque range of the nutrunners used by the system. Multiple accessible torque settings means each tool can provide different torques without significant adjustment to the tool. Chapter 4 showed that only electric-powered, transducer-controlled tools have this feature. Depending on the controller, a single electric-powered, transducer-controlled nutrunner can be set to fifteen or more different torque settings at the flip of a switch. All other tools must be set to a single torque and kept that way.

The longer torque range of the FTNS nutrunners is demonstrated in Figure 7.1. This figures plots the capable torque range of each tool used in Station A (plus a couple more). As shown, the two FTNS have significantly larger torque ranges. A similar plot of tools in Station B would show the four FTNS tools (FTNS 1-4) cover twenty of the twenty-five possible Zeta torque settings. The combined effect of these two factors allow two tools (FTNS 1 and 2) to cover all eleven torque settings between 8.0 and 130 Nm. This is reflected in the third metric of flexibility, the number of available torque settings.

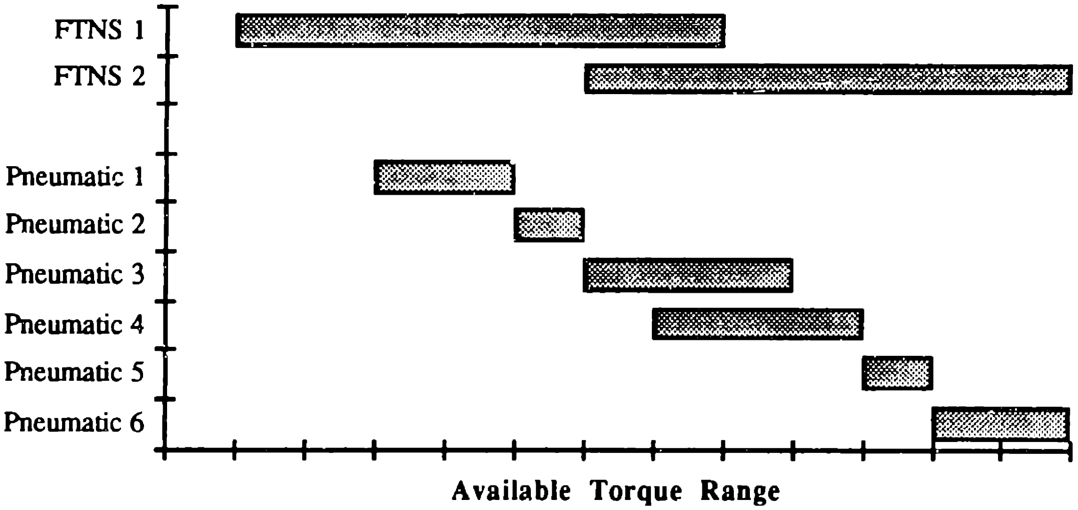

Figure 7.1 Flexibility of Nutrunners (Torque Range)

Product Flexibility

Available torque settings, is the number of different torques (based on Zeta's torque designations*) available with the tools without recalibrating the tools. Table 7.2 shows the two tools of the FTNS cover eleven torque settings while the seven pneumatic tools only

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* Zeta's Fastening Systems Group has identified twenty-five distinct toque settings to be used in automobile assembly. This means the range of installation torques is discrete rather than continuous.

handle one setting apiece. Thus the FTNS tools, without modification, could be used to secure any fasteners with torque requirements within this range of settings.

The number of available torque settings can be used as a measure of the product flexibility of the system. As mentioned in the previous chapter, building an additional vehicle on the same assembly line often requires assigning new torque settings to some stations. This behavior is characterized by Figure 7.2. This figure is based on an analysis of the probability of an additional torque setting being required if an additional fastening operation is added to the station.

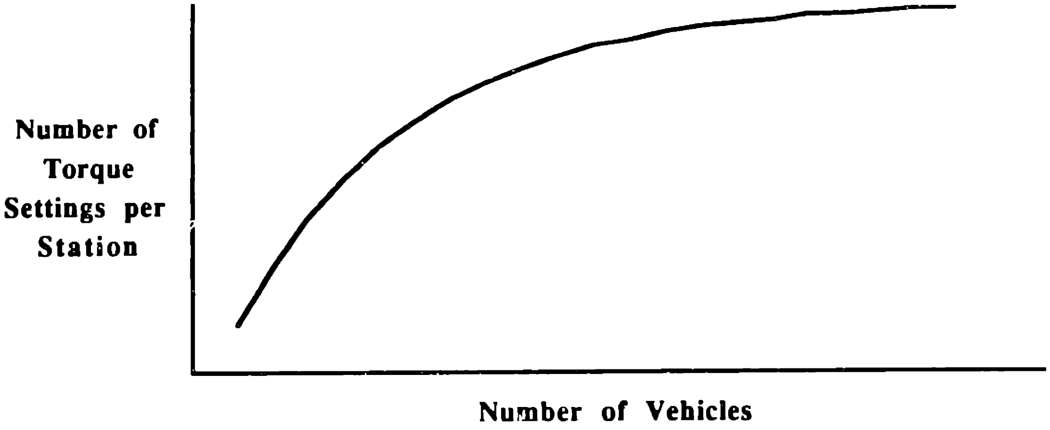

Figure 7.2 Torque Settings per Station for Multiple Vehicles

Thus, a station with a high number of available torque settings would be capable of building more distinct vehicles than a station with a lower number of available settings. It follows, the FTNS, as applied to Station A, increases the product flexibility of the entire LVMS. From the comparisons made in the section, it is clear the FTNS has a higher degree of both product and process flexibility compared to a traditional pneumatic system. The benefits provided by this flexibility will be explored further in the following section comparing the costs of the two nutrunner systems.

7.2 Cost

The cost of a nutrunner system can be broken down into a number of components including initial investment, operating costs and maintenance costs. This analysis parallels Griffith [1992] by assuming the maintenance costs of pneumatic and electric tools are essentially the same. While the larger number of pneumatic tools may cause the maintenance costs for such tools to be larger than tools used by the FTNS, it is unlikely these costs will be significant compared to the investment costs. Similarly, though electric nutrunners have lower operating costs than pneumatic tools (see Table 4.2), the magnitude of the costs are small compared to the initial investment costs. For these reasons the remainder of my analysis will concentrate on investment costs.

Investment costs for a typical station

Table 7.3 presents the estimated investment costs for equipping Station A with either a pneumatic nutrunner system or the FTNS. As shown in the table, the pneumatic system has much lower investment costs - a difference of over $4,700 for this station alone. The high per tool costs of the FTNS leads to higher investment costs than a pneumatic system, despite the benefit of better process flexibility (i.e. fewer tools).

	Pneumatic	FTNS
Number of tools	7	2
Tool cost	$8,785	$9,500
Other costs*	$2,800	$6,800
Total investment cost	$11,585	$16,300

Table 7.3 Investment Costs for Station A

Station B has a similar investment cost structure (Table 7.4). However, in this station the lower number of required pneumatic tools means the cost differential between the two systems is even greater: $8,180 for Station B vs. $4,715 for Station A.

	Pneumatic	FTNS
Number of tools	4	2
Tool cost	$5,020	$8,000
Other costs	$1,600	$6,800
Total investment cost	$6,620	$14,800

Table 7.4 Investment Costs for Station B

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* Other costs include plumbing, regulator and filter for pneumatic tools ($400 per tool) and controllers for FTNS ($6800).

Considering the effects of high investment costs in low-volume production discussed in Chapter 3, this difference in investment costs of the two systems appears significant enough to justify using the pneumatic system. However, up to this point this comparison has ignored the opportunities contained in the product flexibility of the FTNS. The following discussion shows that this aspect of the FTNS can dramatically reduce the investment cost differential between the competing systems.

Effect of multiple products

The previous section demonstrated that the FTNS provides the LVMS with more product flexibility than a pneumatic system. This means an additional vehicle could be added to the FTNS equipped production system without adding more tools. To illustrate this effect, suppose a second vehicle is introduced into the LVMS. Due to design differences between the two vehicles, Station A will be responsible for the installation of the rear suspension on this new car. Similarly, Station B will be responsible for the installation of the heater into the new vehicle. These different processes introduce a number of new torque requirements into each station: two new torques for Station A and four additional for Station B. This means the pneumatic nutrunner system must add an identical number of nutrunners for these new torque requirements. The effects of these change on the investment costs can be see in Tables 7.5 and 7.6 below.

	Pneumatic	FTNS
Number of tools	9	2
Tool cost	$11,295	$9,500
Other costs	$3,600	$6,800
Total investment cost	$14,895	$16,300

Table 7.5 Investment Costs for Station A (Multiple Products)

	Pneumatic	FTNS
Number of tools	8	2
Tool cost	$10,040	$8,000
Other costs	$3,200	$6,800
Total investment cost	$13,240	$16,000

Table 7.6 Investment Costs for Station B (Multiple Products)

As one can see, while the pneumatic system still has a cost advantage over the FTNS (in terms of investment costs), the gap has closed considerably. For this case of two vehicles built on the same line, the cost differentials for Stations A and B are $1,504 and $2,760, respectively. Thus, the product flexibility of the FTNS pays off by significantly reducing the relative investment cost of the FTNS to the point where the two systems are nearly identical in cost. However, there are instances where this product flexibility may not pay off so handsomely. Such an example occurs when the cycle time is significantly reduced.

Effects of cycle time

The previous section stated the product flexibility of the FTNS can reduce the cost disadvantage of this system relative to a pneumatic nutrunner system, to an almost insignificant amount. However, the opposite occurs if the cycle time of the production system is lowered. In such a case the cost disadvantage of the FTNS increases.

Lowering the cycle time would mean a redistribution of tasks among an increased number of workstations. In such an instance the number of operations performed in a single workstation would drop significantly. This can be illustrated by dividing the tasks assigned to Station A into two smaller stations, A' and A". This would represent the reduction of the system cycle time from 15 minutes to approximately 7.5 minutes. The effects of this drop in cycle time on the investment costs of the two nutrunner systems can be seen in Table 7.7 below.

	Pneumatic	FTNS
Station A'		
Number of tools	4	2
Tool cost	$5,020	$9,500
Other costs	$1,600	$6,800
Total investment cost	$6,620	$16,300
Station A"		
Number of tools	5	2
Tool cost	$6,275	$9,500
Other costs	$2,000	$6,800
Total investment cost	$8,275	$16,300
Total investment cost (A' + A")	$14,895	$32,600

Table 7.7 Investment Costs for Stations A' and A"

While the investment cost of the pneumatic system increased by just over $3,330 (due to repeated tools needed in the two stations), the investment cost of the FTNS in this scenario doubled. This increase in cost comes from the fact that completely identical hardware, tools and controllers, would be needed for both of the new workstations. In this case, the investment cost for the FTNS is more than double that of the fixed torque pneumatic system and is unlikely to be justifiable regardless of other advantages.

Effects of Number of Torque Requirements per Station

The key difference between both the multiple vehicle and reduced cycle time scenarios compared to the original scenario (i.e. Station A) is the number of torque requirements within each station. In the case of a shorter cycle time, the smaller number of torque requirements in Stations A' and A" mean fewer pneumatic tools are required to perform the needed rundowns. However, the spread of the torque requirements (i.e. the range of torques) in the smaller stations still require both electric nutrunners of the FTNS to be used in each of the stations. On the other hand, the number of torque requirements increased in Station A when an additional vehicle was introduced to the production system. This required additional pneumatic tools to be purchased.

In this manner, the relative investment costs of the two systems depends on the number of torque requirements per station as shown in Figure 7.3. In the general case shown in the diagram, the number of nutrunners required by the FTNS to cover all assigned torques may be either one or two, depending on exactly which torques are assigned to the station. As the diagram shows, the fewer torques assigned to a particular station, the more expensive the FTNS is compared to a fixed torque pneumatic system. From this, one can conclude the FTNS is better suited for the stations with several torque requirements.

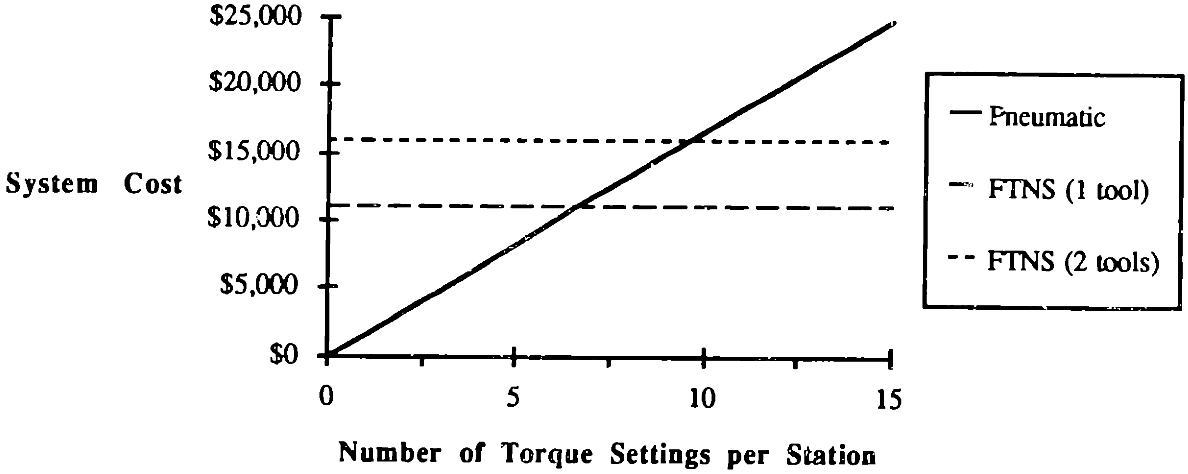

Figure 7.3 Effect of Number of Torque Settings per Station on System Cost

7.2 Quality

The previous chapter stressed the benefits of the FTNS as a method of improving product quality. This quantitative analysis will examine two quality related areas: the torque capability of the individual nutrunners and the process control strategy associated with each nutrunner system

Torque Capability

Chapter 4 introduced torque capability (Cp) as a measure of the accuracy of the torque output of a nutrunner. The capability of a nutrunner is equal to six times the standard deviation of the output torque, expressed as a percentage of the target torque. Both Chapters 4 and 6 sited the lower Cp values of the FTNS tools, compared to pneumatic tools, as evidence of improved product quality. This section will attempt to quantify this effect.

Due to the recent introduction of some of the tools used in this analysis, capability data is not available for all the tools. However, based on discussions with Zeta Fastening Group nutrunner experts, it is possible to generalize the capability of tools used in these nutrunner systems. Electric-powered transducer-controlled nutrunners typically have torque capabilities between 10 and 15%. Pneumatic nutrunners, on the other hand, have capabilities between 15 and 25%. The following analysis assumes the FTNS nutrunners have a capability of 10% and pneumatic nutrunners have a capability of 20%.

Figure 7.4 shows the torque distribution for two tools, one with a 10% capability and the other with 20%. As expected the tool with lower capability value has a tighter spread and is generally closer to the mean (or target) torque value*. This means more of the actual peak dynamic torque values that occur during a rundown will be closer to the target value. This effect is shown even better in Figure 7.5 which shows the percentage of final torque values falling within a range of ± x% of the target torque. For example, over 70% of the rundowns performed by the electric tool (Cp = 10%) are contained within ±2% of the mean compared to less than 40% for the pneumatic tool (Cp = 20%). In other words, if the acceptable tolerance on the dynamic torque were ±2% of the target, then the electric tool would yield acceptable rundowns 70% of the time vs. 40% for the pneumatic tool.

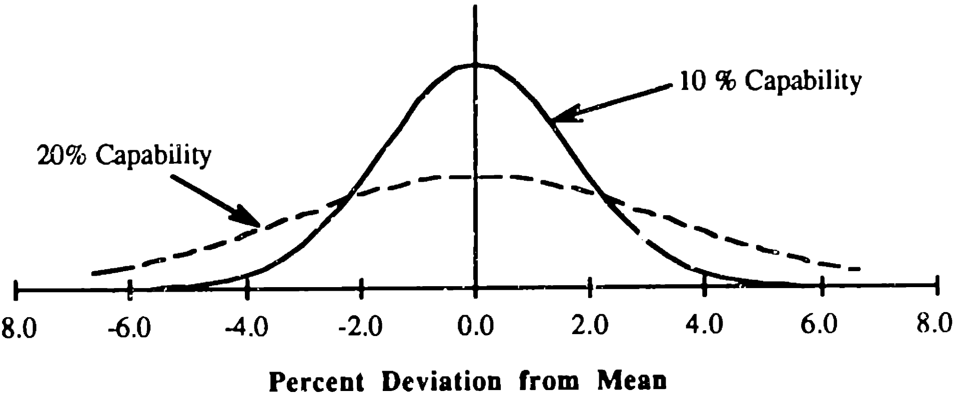

Figure 7.4 Nutrunner Torque Output Distributions

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* For the purpose of this discussion, the torque distributions for both tools are assumed to be centered about the mean. In reality, this need not be true as either tool could produce an off-center distribution.

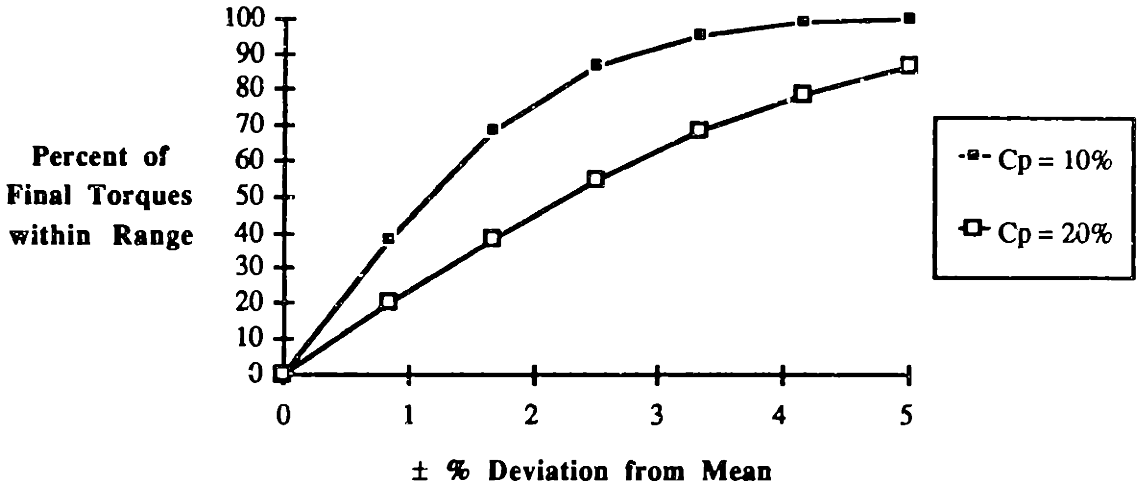

Figure 7.5 Percent of Rundowns within ±x% of the Mean

Torque Process Control

The pneumatic nutrunner system and FTNS also differ in the manner in which torque process control is achieved. This can best be shown by looking at the sampling frequency of rundowns. Table 7.8 summarizes the frequency of measurements under both systems for Station A. As shown, only 42 % of the joints in fastened in this station are examined (these correspond to the eight mandatory compliance operations). In other words, 58% of the fasteners secured in this station are never checked following the initial calibration of the nutrunner. In addition, since these joints are only sampled ten times per shift (32% of vehicles built) this means only 13% of all rundowns are measured for use in torque process control when pneumatic tools are used.

	Pneumatic	FTNS
Percent of joints sampled	42 %	100 %
Percent of vehicles sampled	31 %	100 %
Percent of rundowns sampled	13 %	100 %

Table 7.8 Rundown Sampling Frequencies for Station A

The FTNS, on the other hand, samples *and verifies* each rundown performed. This means not only are peak torque values for all rundowns available for use in data analysis, but each rundown is checked against preprogrammed inspection limits. If the peak torque for a rundown falls outside this acceptable range the system alerts the operator and prompts him to repeat the last rundown. This means that the peak dynamic torque of each fastener leaving the workstation is known to be within predetermined acceptable torque range.

Due to both improved nutrunner torque capability and better process control, the tools of the FTNS produce a more accurate torque output than pneumatic tools. However, the effects effects this improved tools output has on product quality is difficult to quantify.

Previous discussion in this thesis claimed that improved torque accuracy of the nutrunners results directly in improved product quality, as measured by the residual torque of the fastener.* However, there are a number of factors which can contribute to variation in the residual torque of a joint including:

- Power tool torque output variation
- Variation in the parts being assembled
- Interaction from sequential securing of fasteners
- Joint relaxation after the fastener is secured
- Operator variation

Without explaining these five factors, it is clear that the improved torque accuracy of the FTNS only addresses one of a number of factors which can lead to poor quality joints. This makes the positive effects of the better torque accuracy of FTNS difficult to quantify at this level of analysis.

7.4 Time

The final attribute compared between the competing nutrunner systems is time. This section examines the effect of the tool system on two relevant time measures: the time required to perform a rundown and the time required to sample torque data for process control.

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* Residual torque is the torque left in the joint following rundown. This is a measure of the clamping force of the joint and, thus, a measure of the quality of the joint.

Rundown time

The time required to secure a fastener depends on a number of factors including rotational speed of the nutrunner, pitch and thread of the fastener, and the prevailing torque of the joint. To determine the effects of different tool systems on the average rundown time, this section assumes the geometry and dynamics of the joint and fastener are identical for all tools. Thus, the differences in rundown time between different tools can be attributed to differences in rotational speed of the tool.

Figure 7.6 shows the average rundown time of a sample fastener for a number of different nutrunners. From this figure it is difficult to discern any advantage of either the FTNS or pneumatic tool system since the rundown times vary dramatically between tools of each system.

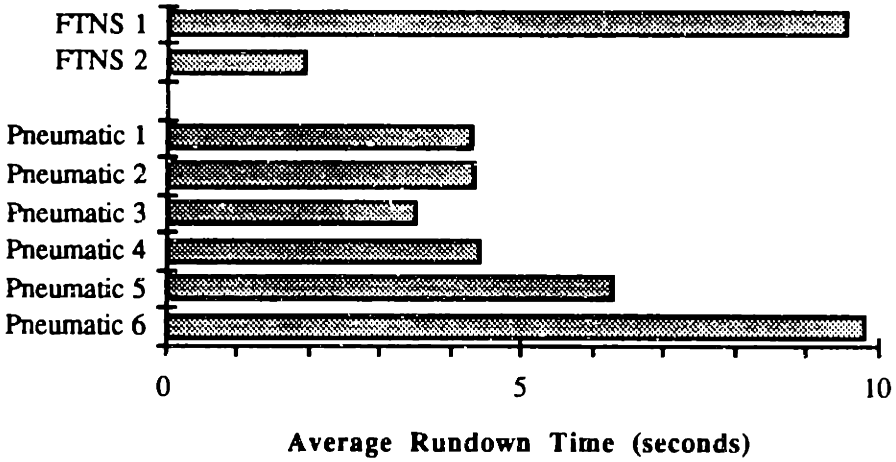

Figure 7.6 Average Rundown Time for Selected Nutrunners

Tables 7.9 and 7.10 use the average rundown times of the tools presented in Figure 7.6 to determine the time to rundown all fasteners in Station A for both tool systems. These calculations show that neither FTNS or pneumatic tools offer any distinct advantage in rundown time.

	Average rundown time	Number of fasteners	Total rundown time
Pneumatic 1	4.32 s	18	77.71 s
Pneumatic 2	4.37 s	0	0
Pneumatic 3	3.54 s	12	42.48 s
Pneumatic 4	4.43 s	6	26.55 s
Pneumatic 5	6.32 s	2	12.64 s
Pneumatic 6	9.33 s	0	0
Total for Station A:			159.4 s

Table 7.9 Rundown Times for Pneumatic Tools in Station A

	Average rundown time	Number of fasteners	Total rundown time
FTNS 1	9.57 s	12	114.8 s
FTNS 2	1.95 s	26	50.57 s
Total for Station A:			165.4 s

Table 7.10 Rundown Times for FTNS Tools in Station A

Sampling Time

Sampling time refers to the time required to measure data for torque process control. As mentioned earlier, the current Zeta torque control system for pneumatic tools requires periodic measurement of residual torque on a select number of joints. Since these tools cannot provide integrated torque measurement (i.e. no tool mounted transducer), pneumatic tool systems require additional equipment and time to make these measurements. The integrated data collection features of the FTNS, on the other hand, allows these tools to automatically collect torque data without additional equipment or operator time.

The effects of these differences are reflected in Figure 7.7*. As the number of joints inspected increases (i.e. increased sampling coverage), the amount of time an operator using a pneumatic system spends making residual torque measurements (as a percent of

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* This figure assumes each residual torque measurement takes 5 seconds and a cycle time of 15 minutes.

cycle time) also increases. Similarly, if the sampling frequency is increased from five to ten units per shift, so does the sampling time for the operator using pneumatic tools. However, in both these instances there is no effect on the sampling time for FTNS - it remains zero for all conditions.

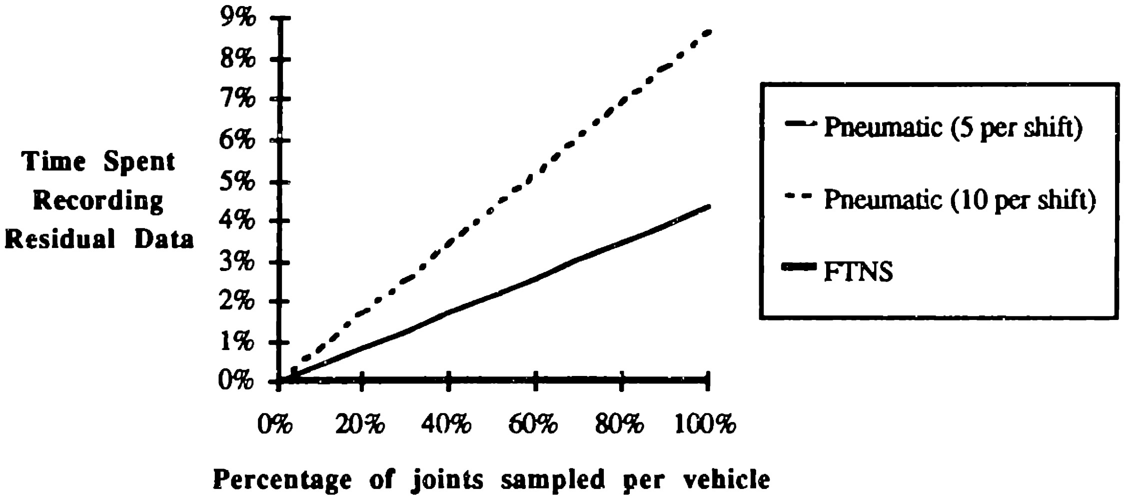

Figure 7.9 Effects of Sampling Rate on Measurement Time

This behavior means that the FTNS is capable of measuring 100% of all rundowns performed. To do this with pneumatic systems would be impossible. Yet even if a low sampling frequency is used, the pneumatic system requires too much of the operators time to perform the measurements on all joints. For this reason most pneumatic torque control systems, including Zeta's, have low sampling coverage and low sampling frequencies.

7.5 Summary

This chapter has quantified some of the advantages of the Flexible Torque Nutrunner system first discussed in the previous chapter over four dimensions of comparison: flexibility, cost, quality and time. These comparisons demosntrated a number of key points worth repeating.

The improved flexibility of the FTNS results in fewer tools and tool models required to outfir a station in the LVMS. Similarly, the higher number of availible torques settings per station improve the product flexibility of the LVMS, as measured by the ability to produce multiple vehicles simultaneously. The combination of these two factors reduces the investment cost differential between the FTNS and pneumatic systems to an almost insignificant level. This chapter showed that this is a direct result of a higher number of torque settings in a station. Thus, the FTNS is best suited for production systems having several different toque requirements in indicual stations.

This chapter also showed that the torque output of the nutrunners used by the FTNS is more accurate than the output of typical pneumatic nutrunners. While the precise benefits of this accuracy with respect to improved product quality could not be quanitifed, the analysis nevertheless showed the benefits would be favorable.

This chapter concluded by examining two time realted measures of performance of the nutrunner systems. This final section showed that neither system has a significant advantage in the time it takes to secure a fastener. However, the FTNS displayed a tremendous advantage in the time required to sample torque data. While pneumatic nutrunners require additional operator time to sample a small number of fastner rundowns, the FTNS can sample all rundowns completed in the station without a time penalty.

The overall conclusion of Chapters 6 and 7 is that the Flexible Torque Nutrunner System is better suited for use in a low-volume production system than traditional nutrunner systems. While the FTNS does have some disadvantages, the benefits this system provides outwiegh these concerns. However, the system is not completely developed and still requires attention in a number of areas. The remaining areas of concern and the potential future for the Flexible TOrque Nutrunner System is discussed in the following concluding chapter

8. Conclusion

The purpose of this thesis was two-fold: first, to present a broad summary of the advantages and disadvantages associated with low-volume automobile assembly, and second, to detail the development of a nutrunner system to be specifically used in low-volume production. The first three chapters of this thesis covered the first purpose. These chapters showed that while most automobiles built in the world today are high-volume vehicles, there are distinct advantages to building low-volume vehicles as well. Chapter 3 then presented a number of factors that make current assembly systems and tools ill-suited for low-volume automobile production. This has lead high-volume automobile manufacturers to develop new processes and equipment for low-volume production.

The last four chapters of the thesis concentrated on just such piece of equipment, the Flexible Torque Nutrunner System. This part of the thesis began with a discussion on the importance of threaded fasteners and nutrunners to automobile assembly, regardless of production volume. Next, this part provided some evidence of the inability of current nutrunner systems to operate effectively in at dramatically lower production volumes. This discussion provided the motivation for the development of a nutrunner system specifically designed for use in low-volume production systems - the FTNS.

Chapter 5 presented an overview of the methodology and tools used to develop theis new nutrunner system. While this chapter discussed some difficulties which arose during the system development, the work on this nutrunnner to date has been successful. This succes was shown in the last two chapters of this thesis which described the FTNS and demonstrated in a number of ways how it is superior to traditional nutrunner systems in a low-volume production system.

However, the development of the Flexible Torque Nutrunner System is not yet complete. At the time of my departure from Zeta, the FTNS was only at the stage of writing the operating specifications. Basically, my work at Zeta has provided a detailed outline of how the FTNS should operate.This means a large amount of the actual design work remains to be done. For instance, writing the actual program code for the system computer's software and determining which nutrunner and controllers (i.e. which supplier) to use.

In addition, some of the features of the FTNS have yet to be specified in the required level of detail. For instance, there are number of details regarding the process reminding function of this system which have yet to be addressed by the development work to date. Some of the more important areas of the FTNS that require more investgation include:

- Content and form of process reminding information
- Integration of FTNS into current torque control system
- Modification of Zeta tool certification procedures to accomodate flexible torque tools
- Method for entering process data for automated torque selection and process reminding

The Future of the Flexible Torque Nutrunner System

Once the development of the Flexible Torque Nutrunner System is completed, the system will provide Zeta Motor Company with an important piece of the puzzle of low-volume automobile assembly. Coupled with the Low Volume Manufacturing System, the FTNS will allow Zeta to reap the benefits of low-volume vehicles in a more cost effective manner. However, the FTNS has a number of potential applications outside of low volume-production. Two such applications are in the pilot plant for use in building and gathering data on prototype vehicles and in the repair areas of high-volume assembly plants. Other applications could include anywhere in Zeta's operations which require quality fastener rundowns over a number of torque ranges.

In addition, the FTNS will provide Zeta with considerable knowledge that can be applied to high-volume vehicle produciton. As the price of electric-powered, transducer-controlled drops, more of these tools will likely be used in high-volume production. When this occurs, the experience Zeta has gained from using these tools as part of the FTNS will be invaluable. Similalrly, lessons learned from the process reminding feature of the FTNS might lead to improved broadcasting of process informaiton on high-volume lines.Thus, when complete the Flexible Torque Nutruner System will have a significant impact on a broad area of Zeta Motor Company's operations.

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Appendix A Torque Process Control at Zeta Motor Company

The torque process control system used at Zeta Motor Company has two distinct parts: a Torque Process Potential Study and Torque Surveillance. A Torque Process Potential Study (TPPS) is performed at the start-up of vehicle production (i.e. beginning of the model year) on each joint in the vehicle. The purpose of this study is to (1) set the nutrunners to proper mean torque output , (2) determine the process potential (or capability) of the operation, and (3) calculate the dynamic or residual inspection limits for the process. Torque Surveillance, on the other hand, occurs daily during production and involves measuring the torque on a select set of fasteners to ensure torque remains in process control. Torque Surveillance can be seen as the heart of the torque process system. For this reason it is described in more detail below.

Torque Surveillance

Torque surveillance involves collecting data on the peak torque on a particular fastener. These measurements can be conducted in two ways, each resulting in a different form of torque. Transducer equipped tools, such as electric-powered transducer-controlled nutrunners, provide real-time data collection of the torque imparted to the fastener by the tool. This torque is called dynamic torque. Nutrunners without transducers cannot provide dynamic torque data. Instead, measurements must be made of the residual torque of the fastener. This is done by using a transducer equipped manual torque wrench to measure the torque at which the fastener begins to rotate in the tightening direction. Since most tools currently used in automotive assembly lack transducers, this discussion will concentrate on residual torque surveillance.

The manner in which torque surveillance is carried out also depends on the joint in question. Each joint in a vehicle is classified as one of three types of fastening operations: mandatory, significant and unclassified. Zeta's Fastening Systems Group defines these joints in the following manner. A mandatory operation contains a "critical characteristic" which can affect compliance with government regulations or safe vehicle operation. For instance, seat belt restrains and suspension mounting bolts are both mandatory operations. Significant operations are those operations which are important to customer satisfaction, but do not threaten the operation or safety of the vehicle. Unclassified operations, include all other fasteners in a vehicle. Each of these operations is handled differently by the torque surveillance part of torque process control.

For mandatory operations, torque surveillance is carried out in the following manner:

1.) Two sets of five samples of residual torque are collected every shift
2.) These samples are compared to predetermined residual torque limits. If any of the torque values are below these residual limits then five ore samples are taken.
3.) If none of these additional samples are outside of the residual limits then the frequency of data collection is increased to five torque samples every hour for the next two hours. Otherwise the following corrective actions are taken:
    - Each future unit built must be hand checked with a manual click torque wrench set to the lower residual limit. This will ensure all future units have acceptable residual torque.
    - Check each previously built unit since the last residual torque sampling with a manual click torque wrench. Fasteners with insufficient residual torque will thus be tightened to the minimum acceptable level.
    - Continue these actions until the torque is shown to be in process control (i.e. consistently within residual limits).

For significant operations, torque surveillance is carried out in the following manner:

1.) One set of five samples of residual torque is collected every shift
2.) These samples are compared to predetermined residual torque limits. If any of the torque values are below these residual limits then five ore samples are taken.
3.) If none of these additional samples are outside of the residual limits then the frequency of data collection is increased to five torque samples every hour for the next two hours. Otherwise the following corrective actions are taken:
    - Each future unit built must be hand checked with a manual click torque wrench set to the lower residual limit. This will ensure all future units have acceptable residual torque.
    - Check each previously built unit with a manual click torque wrench until thirty units in a row are found with the proper torque.
    - Continue these actions until the torque is shown to be in process control (i.e. consistently within residual limits).

For unclassified operations there is no regular torque surveillance procedure. These operations are assumed to be in torque process control following initial set-up of the tool(s) as part of the TPPS. The only methods by which an insufficiently torqued unclassified fastener can be discovered are the following:

- Operator notices difference in torque reaction or motor sound during rundown
- Fastener is visably loose and discovered by an operator
- Fastener fails or loosens following assembly. in this case the discovery may occur at the dealership or by the final customer.

Zeta Motor Company Standard Torque Specifications

Zeta's Fastening Systems Group has standardized the torque specifications used in the assembly of all vehicles built at its North American plants. The following codes are used to designate the target torque of a particular fastener or the output of a nutrunner.

Torque Code	Torque (Nm)
N01	0.8
N02	1.0
N03	1.3
N04	1.7
N05	2.2
N1	2.8
N2	3.7
N3	4.8
N4	6.2
N5	8.0
N6	10.5
N7	13.5
N8	17.5
N9	22.5
N10	27.5
N11	35.0
N12	47.5
N13	62.5
N14	80.0
N15	103.0
N16	133.0
N17	175.0
N18	225.0
N19	275.0
N20	350.0

Appendix B Assembly Operator Interview Questions

General / Background

What is your name?
How long have you worked at Ford?
What is your current job?
How long have you been doing it?

Pacing

On a typical high volume assembly line, it does not take long for a worker to develop a rhythm to his work due to the small number of tasks and frequent repetition. This allows a worker to pace himself through his work and be sure he will be done in the allowed time. On a low volume assembly line it will be more difficult for a worker to pace himself due to the larger number of tasks and fewer repetitions. For this reason we are considering developing some form of pacing aid to use during training and first few weeks of production. I would like to talk about any ideas you may have on this subject.

In your current job do you consciously pace yourself in order to finish your work in the allowed time or have you developed a "feel" for the job to the point where you don't even think about your pace?

Describe how you currently pace yourself.

What do you like or dislike about this method?

Do you see any way to improve your ability to pace yourself?

Suppose you were working on a very low volume assembly line that had a cycle time (time between successive units) of 10 to 15 minutes. At this volume the vehicle would be either stationary or barely moving.

In this situation do you feel it could be difficult to consistently pace yourself in a way to ensure you completed units within the allowed time?

If so, do you have any suggestions on how to aid you and other workers in pacing themselves?

Computer Interface

Computers are becoming more and more important to manufacturing these days. It is likely any low volume manufacturing system would use computers to a larger degree than typically seen today in Zeta. This could mean assembly line workers would be using computers in their day to day work more than ever before. In order to make any future computer system as user friendly as possible, I would like to know some of you opinions on using computers.

In either your current job or in some past position have you used computers in a plant setting? If so :

How did you use the computer? Describe a typical session/interaction.

What did you like about this?

What did you dislike about using a computer in the current set-up?

Suppose you were part of a team looking at buying a computer system for use on the assembly plant floor. As one of the union(worker?) team members, you are interested in making sure any new system is received well by the workers.

What would be your main concerns with respect to computer - worker interaction/interface?

What features would you look for or look to avoid? (i.e. touch screens, multi color, keyboard, mouse, etc...)

Process Reminding / Training

If Zeta were to build a low volume assembly line two major differences from normal assembly lines would be more operations per car for each worker and the ability to build several different vehicles on the same line simultaneously. A likely scenario would be an assembly line with a cycle time on the order of 10 to 15 minutes building four completely different vehicles with platform build rates between 5 per hour and 1 per week.

To better imagine what this may be like one can picture oneself performing your current job as well as the jobs of people immediately ahead and behind you on the assembly line -- probably as many as twenty independent tasks per worker. If you were to combine this situation with the possibility of running several unique vehicles down the same assembly line a concern arises whether the workers will be able to memorize all their tasks for all the different vehicles

In order to help deal with this potential problem we are considering some form of process reminding (probably computer based) that would help the worker remember what to do and when to do it for any of a number of vehicles he may build.

Do you think such a reminding system would be helpful to you in the situation described?

What information do you think you would need? (i.e. would a simple list be sufficient or would a more detailed reminder be helpful -- especially for vehicle built only a few times a week)

In addition to dealing with possible problems of the normally assigned worker remembering all his tasks, we are looking at ways to help substitute and new workers learn their jobs more quickly in such a complex system. Suppose one of you co-workers has called in sick, and you have been chosen to take over his/her job for the day. Since there are several different vehicles being built, the supervisor cannot walk you through each operation for each vehicle.

What information do you need to be able to carry out the new job?

What if this had been a job which you had performed before as a substitute but the last time you did it was two weeks ago?

How would your information needs differ from the previous case?

Appendix C Ranked Customer Needs

The following matrix gives the results of the customer needs surveys. The average, minimum, maximum and range of responses on a 1-9 (9 = very important). During the evaluation of these needs different ranking systems were used. The most common was ranking by average response. However, this example shows the needs ranked by the best response, then by the average response.

		avg.	max	min	R
1.)	*The system ensures high quality vehicles are built*	8.7	9	8	1
2.)	*The system can be used in a normal factory environment*	8.5	9	8	1
3.)	*The employee feels the system is helping him*	8.5	9	8	1
4.)	*The system allows each tool to be used for several torques and fasteners on the same vehicle*	8.3	9	8	1
5.)	*The system ensures only high quality vehicles leave the station*	8.3	9	7	2
6.)	*The system controls torque on all joints with high precison & accuracy*	8.3	9	7	2
7.)	*The system does not interfere with the employee's ability to perform his job.*	8.3	9	7	2
8.)	*The system helps employees perform their jobs in a low volume scenario*	8.0	9	7	2
9.)	*The system provides information on mandatory & signficant requirements to the employee*	8.0	9	7	2
10.)	*Tools are rugged and durable*	8.0	9	7	2
11.)	*The system allows in station repair of vehicles*	8.0	9	5	4
12.)	*The computer display is easy to see and understand.*	7.8	9	7	2
13.)	*The system displays information in a form that is quick to read and understand.*	7.8	9	7	2
14.)	*The employee knows if he has completed all his tasks correctly and completely.*	7.8	9	7	2
15.)	*Nutrunners are easy to use.*	7.8	9	7	2
16.)	*The system is simple to use & understand*	7.8	9	5	4
17.)	*The system can survive and operate in a plant environment*	7.8	9	5	4
18.)	*The system can be used by employees with no computer experience*	7.5	9	5	4
19.)	*The computer interface is user friendly*	7.5	9	3	6
20.)	*Users can recover from computer entry mistakes easily and quickly*	7.5	9	3	6
21.)	*Employees can move from joint to joint without waiting for system*	7.3	9	5	4
22.)	*The system provides accurate, up to date information*	7.3	9	4	5
23.)	*System helps to cultivate responsible and aware employees*	7.3	9	4	5
24.)	*The system is easy to use*	7.3	9	3	6
25.)	*The user spends a minimal amount of time searching for button or key to press.*	7.3	9	3	6
26.)	*The system allows the same tools to be used for assembly, disassembly, and repairs.*	7.3	9	3	6
27.)	*The system takes a minimal amount of time to prepare for next vehicle*	7.0	9	4	5
28.)	*System provides additional information for rarely built units & options*	6.8	9	4	5
29.)	*Substitute employees are able to perform jobs by themselves*	6.8	9	4	5
30.)	*The system provides access to data from remote terminal(s)*	5.5	9	1	8

		avg.	max	min	R
31.)	*The system provides information based on expected needs of users*	4.8	9	3	6
32.)	*The system can control tools of different manufacturers*	8.0	8	8	0
33.)	*The employee is aware if rundown is successful or unsuccessful*	7.8	8	7	1
34.)	*Employees can switch sockets from tools with minimal effort*	7.8	8	7	1
35.)	*Employees can use system while wearing normal work gloves*	7.8	8	7	1
36.)	*The system controls tool dynamic torque within B&AO specs*	7.5	8	7	1
37.)	*Employees can switch from tool to tool with minimal effort*	7.5	8	7	1
38.)	*The system minimizes disruptions caused by absent or substitute employees*	7.5	8	6	2
39.)	*The system allows an untrained employee to learn a job in a few minutes*	7.5	8	6	2
40.)	*The system provides employees with specific information on vehicle build process while they are assembling the vehicle.*	7.3	8	6	2
41.)	*The system provides feedback to employee on quality of work*	7.3	8	6	2
42.)	*The system requires a minimal amount of user input*	7.3	8	5	3
43.)	*The system provides information on proper sequence of tasks*	7.0	8	6	2
44.)	*The employee knows if a problem has occured*	7.0	8	6	2
45.)	*The system correctly determines which torque rundown profile to use for current joint*	7.0	8	5	3
46.)	*System provides information to help employees identify correct part(s) to install*	6.8	8	6	2
47.)	*The system provides reports based on individual user needs*	6.8	8	6	2
48.)	*The system has low development and operating costs*	6.8	8	5	3
49.)	*The employee is alerted if torque process is going out of process control*	6.8	8	4	4
50.)	*The system can be used with a minimum of additional training*	6.8	8	3	5
51.)	*The system collects torque data on "rejects"*	6.7	8	5	3
52.)	*The system collects data on repairs and assembly problems*	6.7	8	5	3
53.)	*The system provides information on which part(s) to install next*	6.5	8	6	2
54.)	*The system helps employees pace their work*	6.5	8	5	3
55.)	*The system provides summary reports for different users*	6.5	8	5	3
56.)	*Employees have time to prepare for next vehicle*	6.3	8	4	4
57.)	*The system helps create a friendly & productive workplace environment*	6.3	8	4	4
58.)	*The system information can be quickly updated as necessary*	6.0	8	3	5
59.)	*The system provides information for all possible vehicle option and platform combinations*	6.0	8	3	5
60.)	*Tool rotation can be easily reversed at the tool by the employee*	5.8	8	1	7

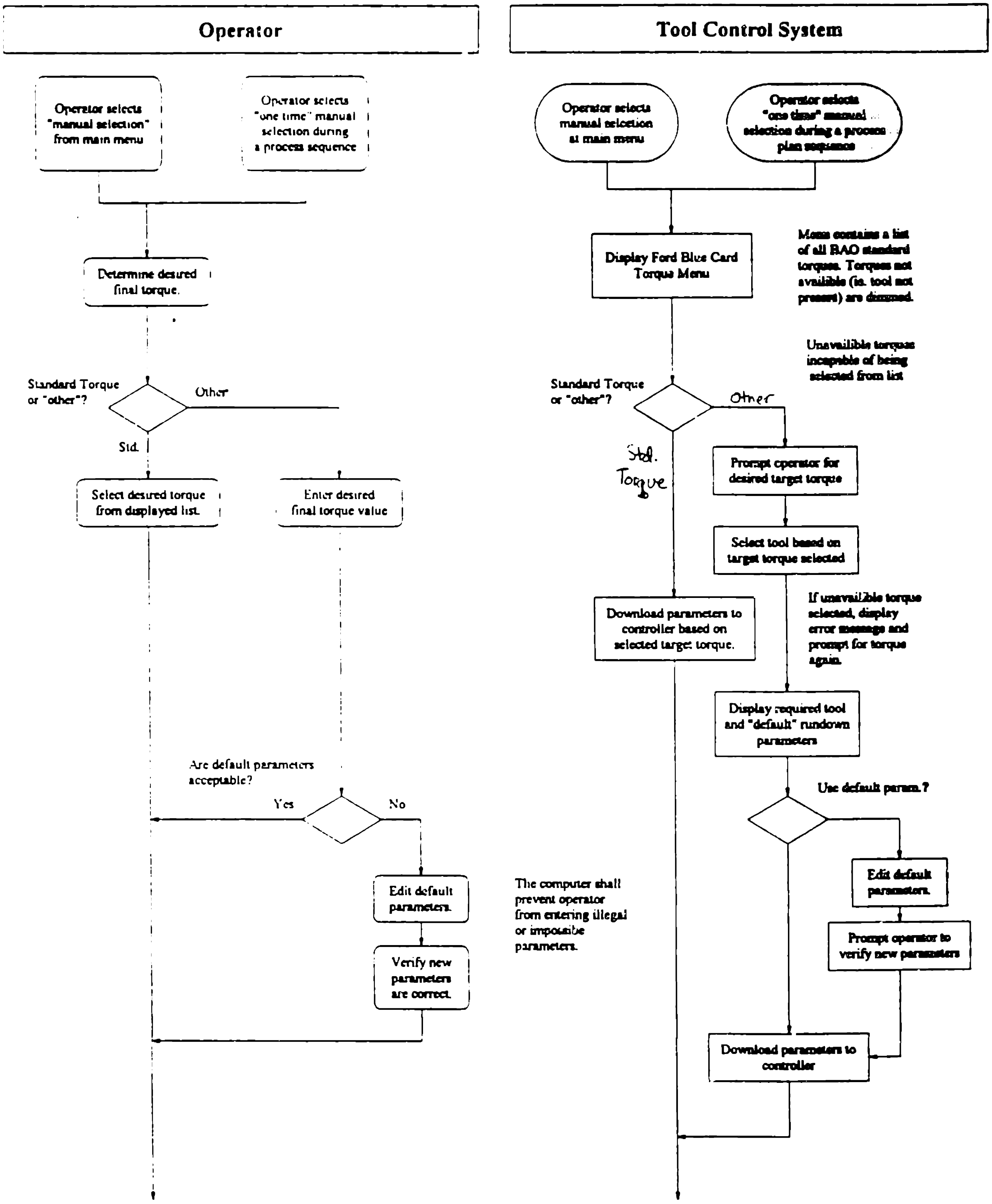
		avg.	max	min	R
61.)	*Employees can easily calibrate & set-up tools / system*	5.5	8	1	7
62.)	*The system correctly determines which joint worker is currently working on*	5.3	8	3	5
63.)	*The system distinguishes between normal rundowns, disassemblies and repair rundowns*	5.0	8	2	6
64.)	*The system provides additional information for difficult and government mandated tasks*	4.8	8	1	7
65.)	*The system allows all joints in a vehicle to be fastened with a minimum of tools*	7.0	7	7	0
66.)	*The system records peak dynamic torque data for mandatory and significant fastening operations.*	6.5	7	6	1
67.)	*The system collects data on fastener rundowns.*	6.3	7	5	2
68.)	*The system collects torque, time and angle data during rundown*	6.3	7	5	2
69.)	*The system retains an optimally sized set of rundown data*	6.0	7	5	2
70.)	*The system is capable of performing statisitical analysis of fastener rundown data.*	6.0	7	5	2
71.)	*The system helps employees learn new methods/processes*	5.8	7	2	5
72.)	*The system provides information on tools and fixtures to use*	5.5	7	3	4
73.)	*The system provides a method to pace work on stationary vehicles*	5.3	7	4	3
74.)	*The system has additional process information availible on demand*	5.3	7	2	5
75.)	*The system provides means to check pace vs. time/work left.*	5.0	7	2	5
76.)	*The system allows employees freedom in how to perform their allocated work*	5.0	7	2	5
77.)	*The system allows employees flexibility in the sequence of tasks performed (when allowable)*	4.8	7	2	5
78.)	*The system provides employees with flexibility to locate tools, sockets and stock.*	4.5	7	3	4
79.)	*The system is accessible to users off the plant floor*	4.5	7	1	6
80.)	*The system provides employees with information on how to perform tasks*	4.8	6	3	3
81.)	*Process information accurately reflects what is done by employees*	4.5	6	3	3
82.)	*Display can be seen from entire working area of worker*	4.5	6	2	4
83.)	*The system allows for multistage tightening techinques*	4.3	6	2	4
84.)	*The system interfaces with appropriate current information systems*	4.7	5	4	1
85.)	*System provides information about next vehicle(s) before it arrives*	4.3	5	3	2

Appendix D Concept Scoring Matrix for Torque Selection

	Concept		
Ranked Customer Needs	**A**	**B**	**C**
The system ensures high quality vehicles are built	3	3	3
The system can be used in a normal factory environment	3	3	3
The employee feels the system is helping him	2.7	3	3
The system allows each tool to be used for several torques and fasteners on the same vehicle	3	3	3
The system ensures only high quality vehicles leave the station	4	4	3
The system controls torque on all joints with high precision & accuracy	3	3	3
The system does not interfere with the employee's ability to perform his job.	3	3	3
The system helps employees perform their jobs in a low volume scenario	3	3	3
The system allows in station repair of vehicles	2	3	3
The employee knows if he has completed all his tasks correctly and completely.	4	3	3
Nutrunners are easy to use.	3	3	3
The system is simple to use & understand	3.5	3.5	3
The system can be used by employees with no computer experience	2	3	3
Employees can move from joint to joint without waiting for system	4	4	3
System helps to cultivate responsible and aware employees	2.5	3	3
The system is easy to use	2.5	2.7	3
The user spends a minimal amount of time searching for button or key to press.	4	4	3
The system allows the same tools to be used for assembly, disassembly, and repairs.	2	2	3
The system takes a minimal amount of time to prepare for next vehicle	2	2	3
Substitute employees are able to perform jobs by themselves	3.5	3.5	3
The employee is aware if rundown is successful or unsuccessful	3	3	3
Employees can switch sockets from tools with minimal effort	3	3	3
Employees can use system while wearing normal work gloves	3	3.5	3
The system controls tool dynamic torque within B&AO specs	3	3	3
Employees can switch from tool to tool with minimal effort	3	3	3
The system minimizes disruptions caused by absent or substitute employees	3.5	3.5	3
The system allows an untrained employee to learn a job in a few minutes	3.5	3	3
The system requires a minimal amount of user input	2.7	2.7	3
The system correctly determines which torque rundown profile to use for current joint	4	4	3
The system has low development and operating costs	2	2.5	3
The employee is alerted if torque process is going out of process control	4	3	3
The system can be used with a minimum of additional training	3	3	3
The system collects torque data on "rejects"	4	3	3
The system information can be quickly updated as necessary	3	3	3
Employees can easily calibrate & set-up tools / system	1	2	3
The system correctly determines which joint worker is currently working on	4	3	3
The system distinguishes between normal rundowns, disassemblies and repair rundowns	4	3	3
The system allows all joints in a vehicle to be fastened with a minimum of tools	3	3	3
The system records peak dynamic torque data for mandatory and significant fastening operations.	4	3	3
The system collects data on fastener rundowns.	3.5	3	3
The system collects torque, time and angle data during rundown	3	3	3
The system allows employees freedom in how to perform their allocated work	1	3	3
The system allows employees flexibility in the sequence of tasks performed (when allowable)	1	3	3
The system provides employees with flexibility to locate tools, sockets and stock.	3	2.5	3
The system allows for multistage tightening techniques	4	3	3
Average Weighted Score:	3.03	3.05	3.00
Rank:	2	1	3

Appendix E Operational Flowcharts for Flexible Torque Nutrunner System

Normal Operation (Manual Torque Selection)



Menu contains a list of all BAO standard torques. Torques not availible (ie. tool not present) are dimmed.

Unavailible torques incapable of being selected from list

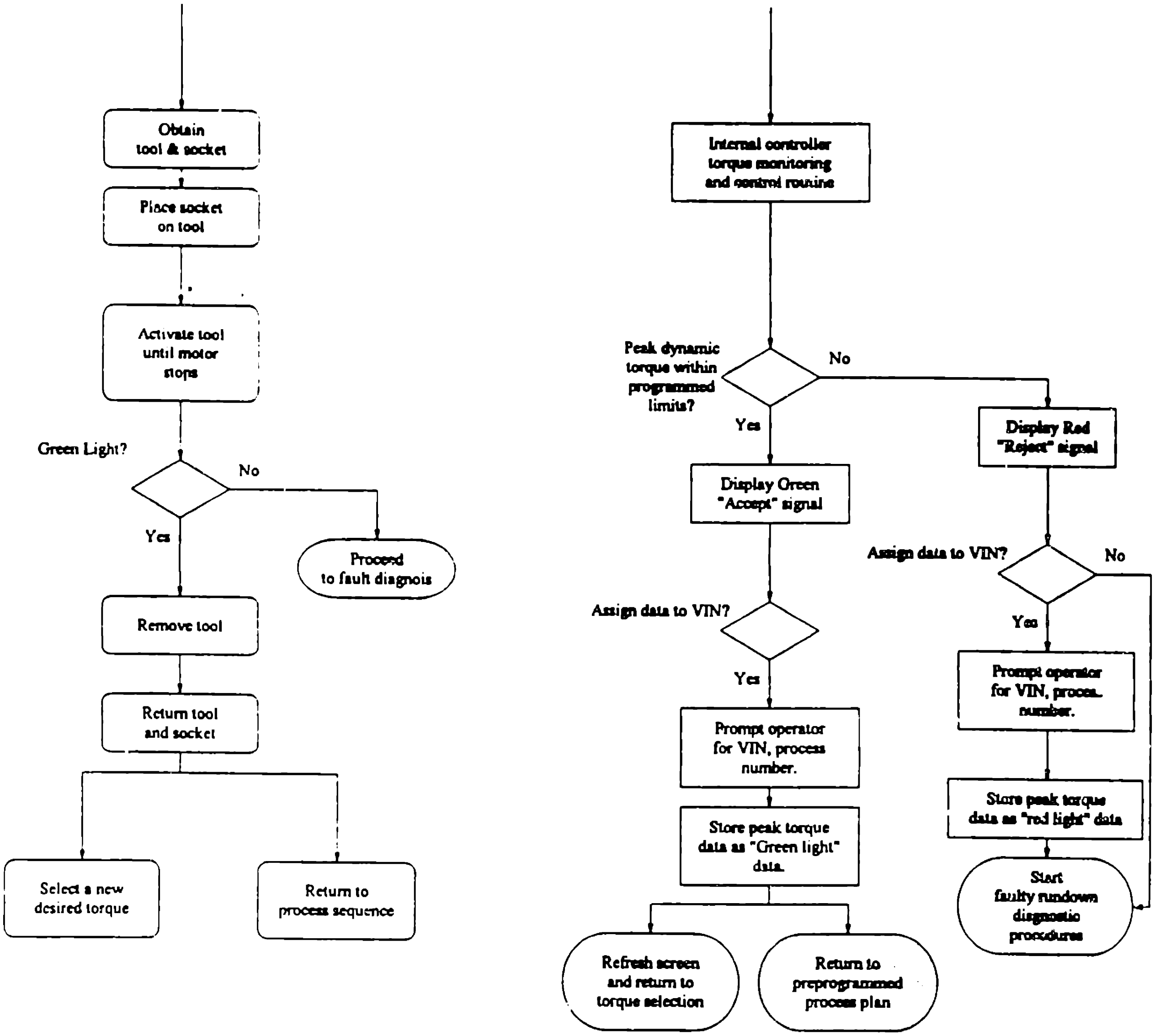
If unavailable torque selected, display error message and prompt for torque again.

The computer shall prevent operator from entering illegal or impossibe parameters.

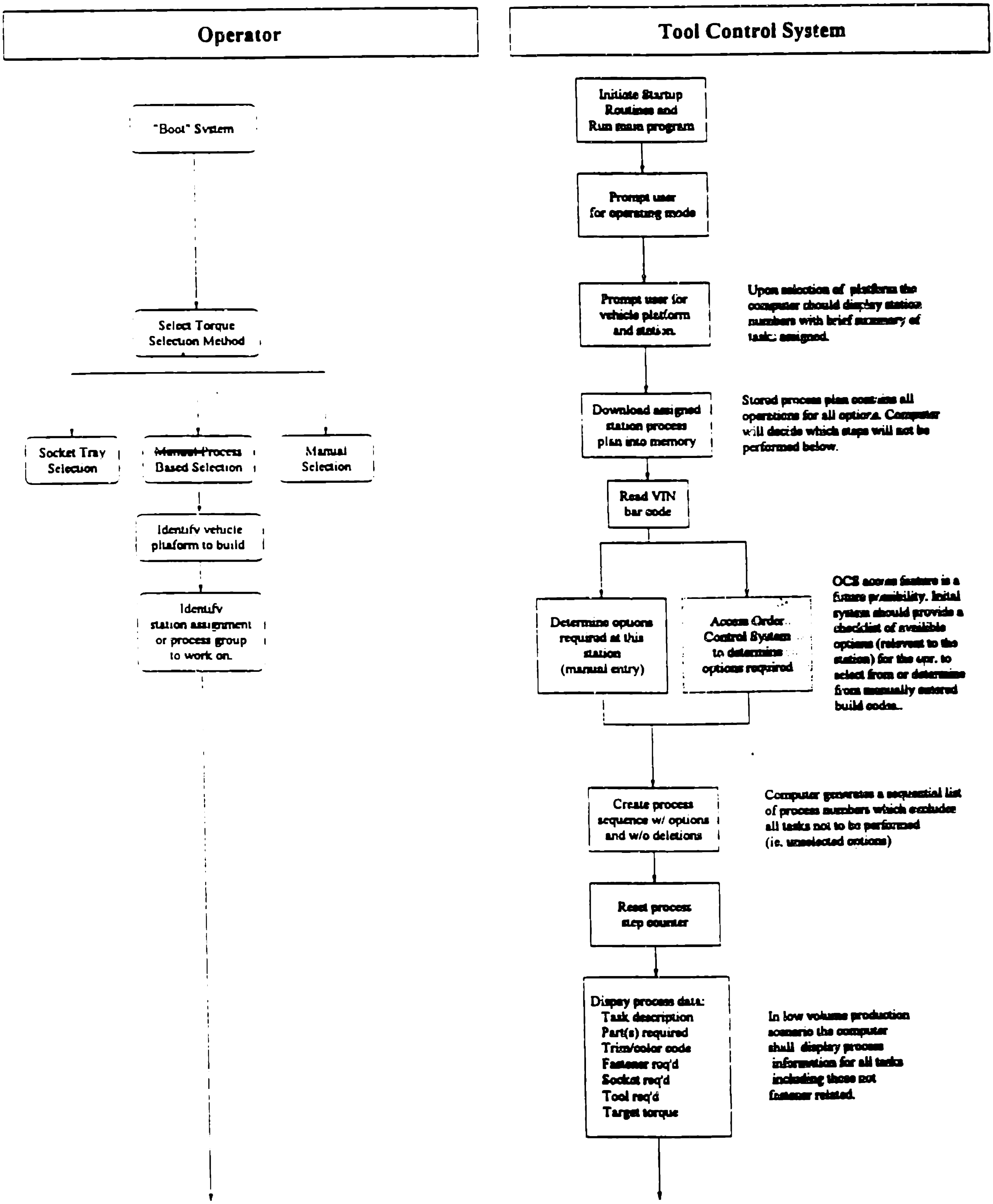
Normal Operation (Manual Torque Selection)

Operator

Tool Control System



Normal Operation (Process Based Torque Selection)



Upon selection of platform the computer should display station numbers with brief summary of tasks assigned.

Stored process plan contains all operations for all options. Computer will decide which steps will not be performed below.

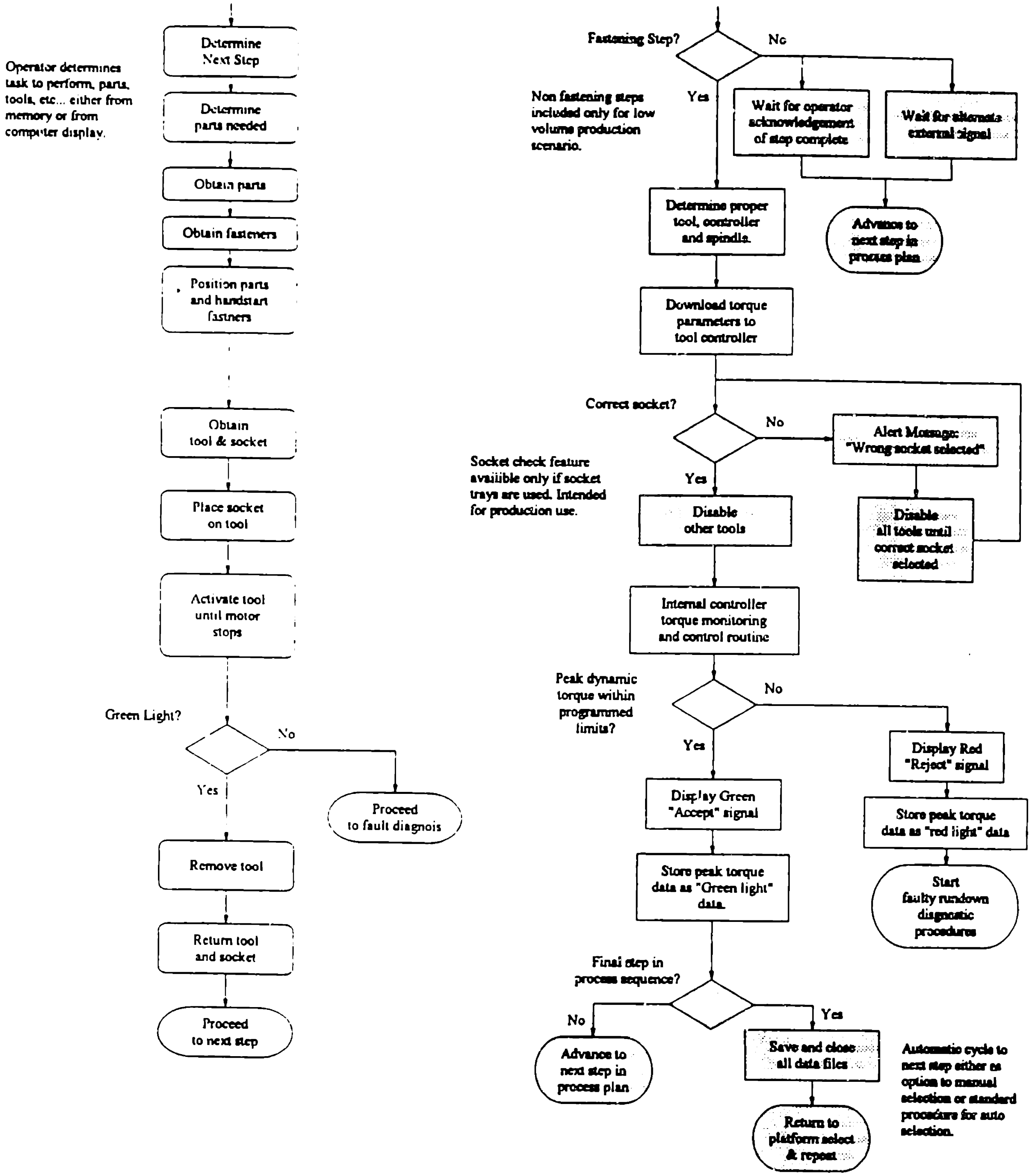
OCS access feature is a future possibility. Initial system should provide a checklist of available options (relevant to the station) for the opr. to select from or determine from manually entered build codes.

Computer generates a sequential list of process numbers which excludes all tasks not to be performed (ie. unselected options)

In low volume production scenario the computer shall display process information for all tasks including those not fastener related.

Normal Operation (Process Based Torque Selection) (con't)

Operator | **Tool Control System**



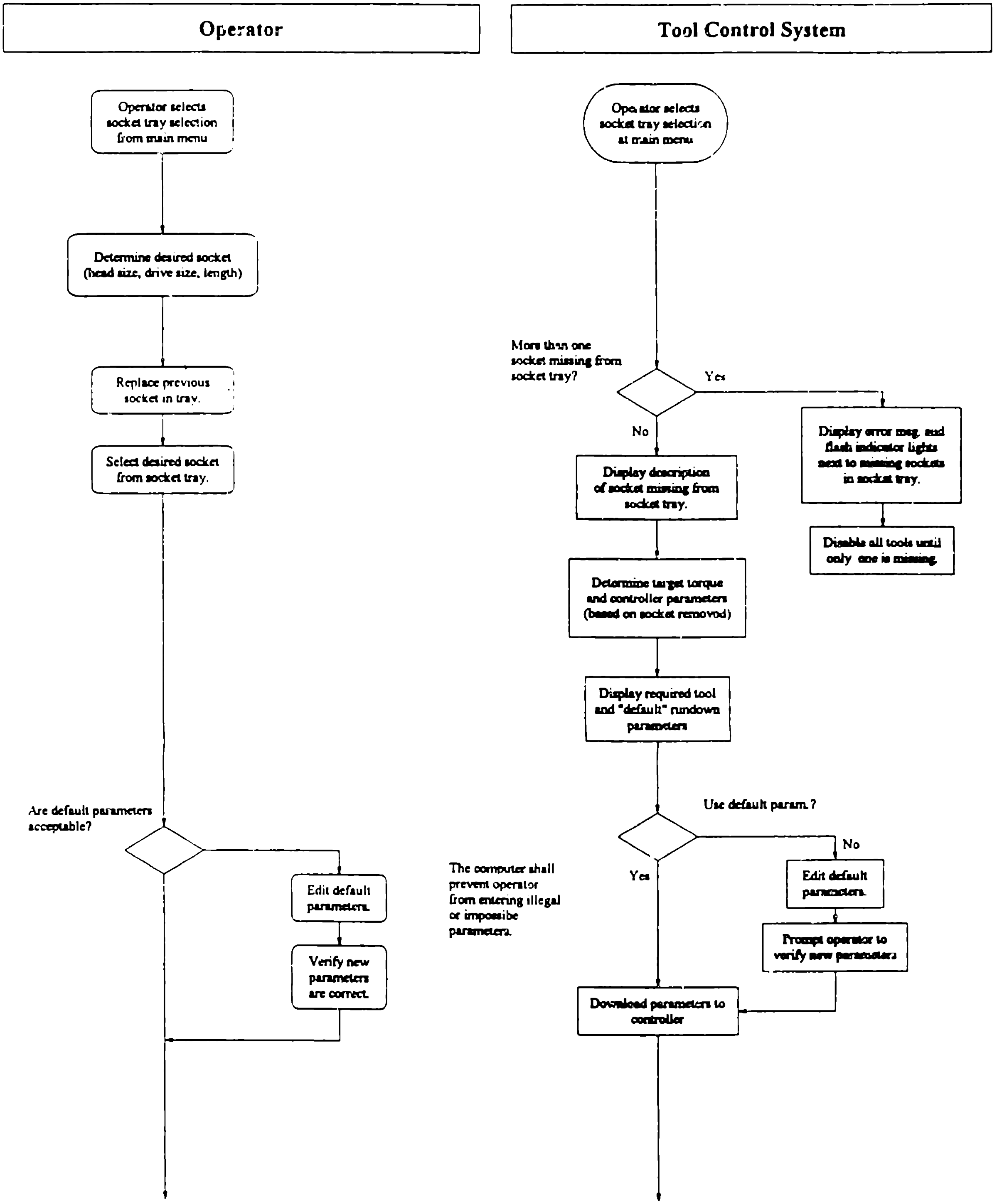
Operator determines task to perform, parts, tools, etc... either from memory or from computer display.

Non fastening steps included only for low volume production scenario.

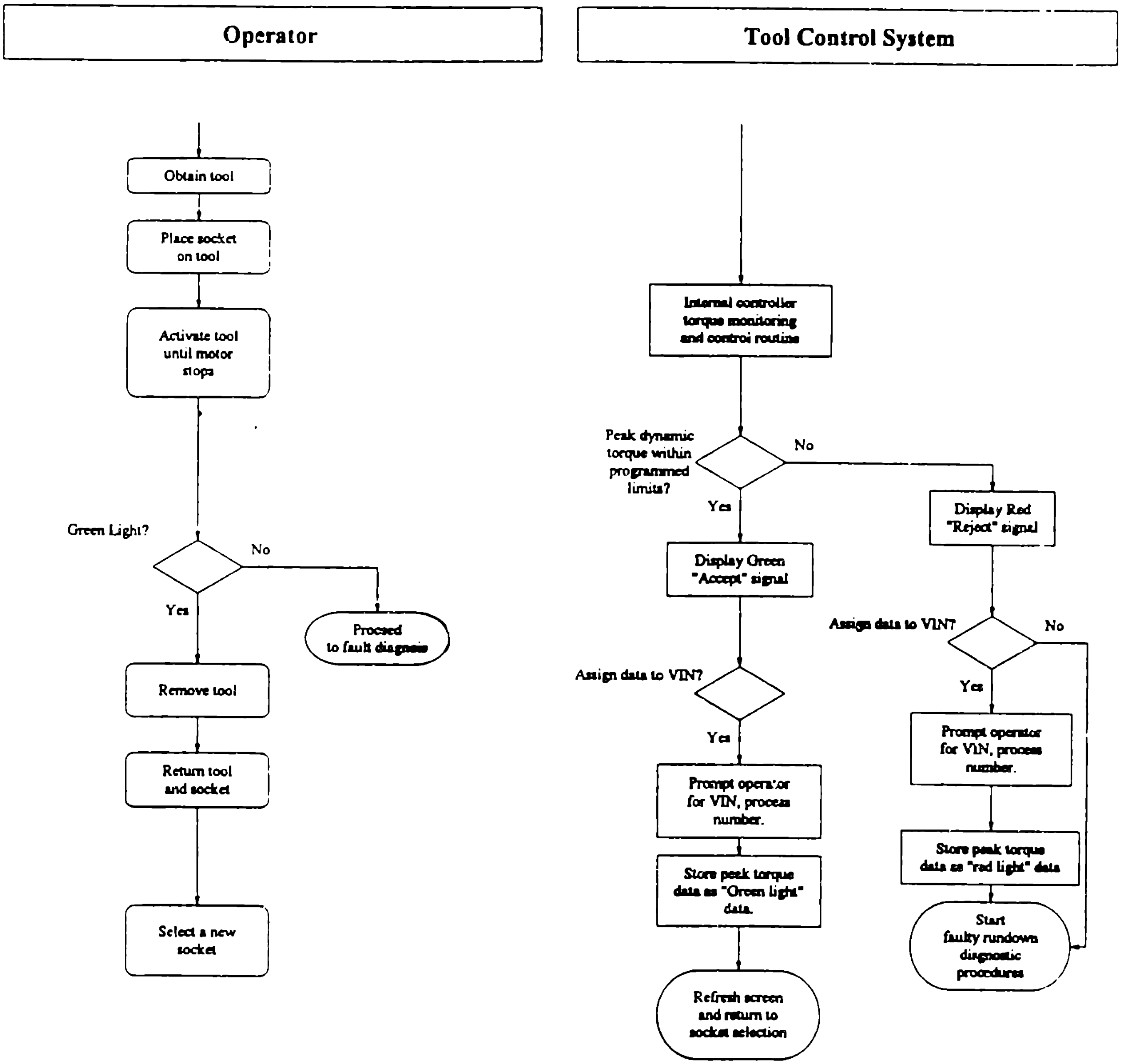
Socket check feature availible only if socket trays are used. Intended for production use.

Automatic cycle to next step either as option to manual selection or standard procedure for auto selection.

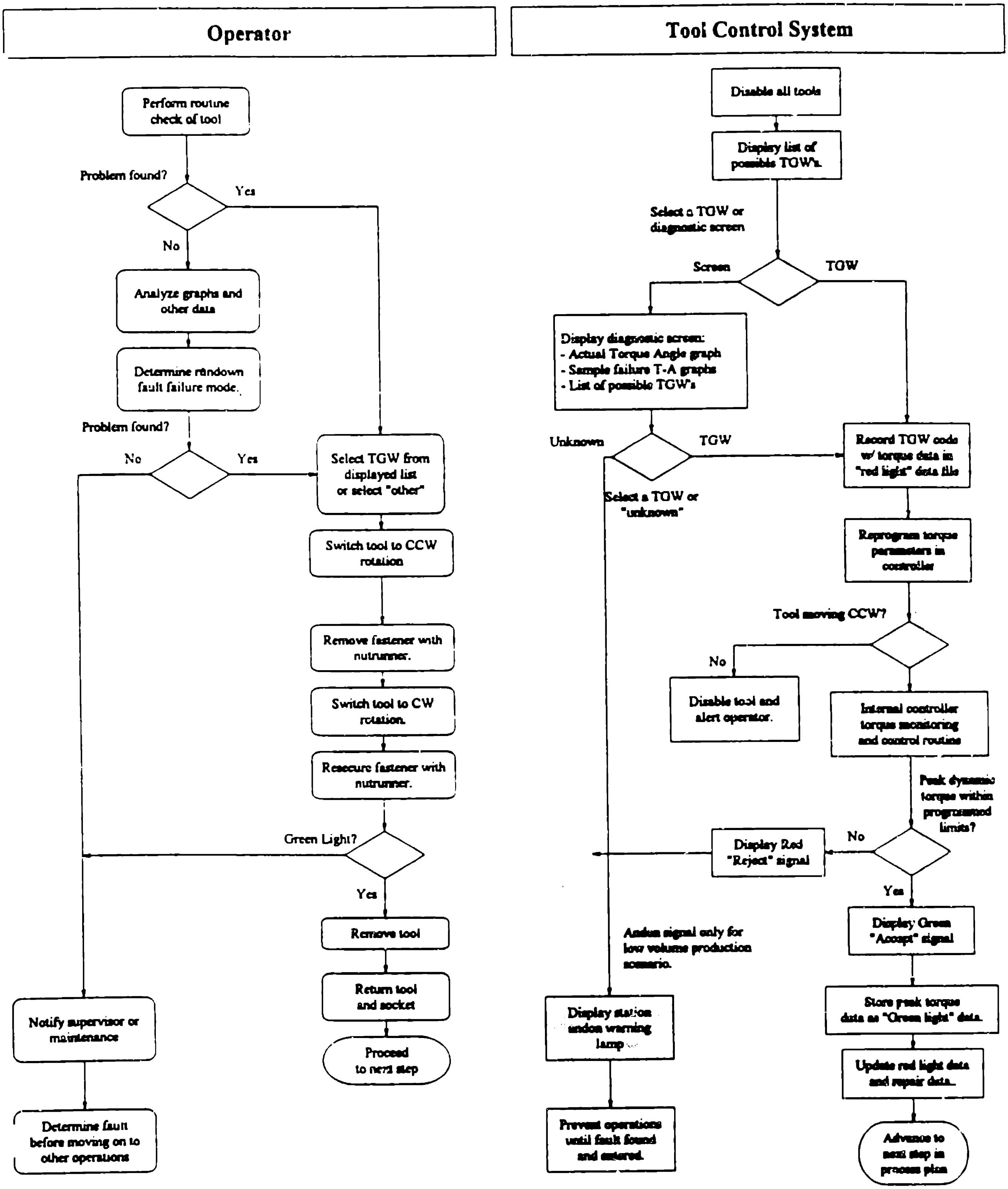
Normal Operation (Socket Tray Selection)



Normal Operation (Socket Tray Selection)



Faulty Rundown Diagnosis & Repair



Appendix F Task Allocation for Sample Workstations

Station A: Front Suspension Installation

Operation Description	Torque Setting	Number of fasteners
Crossmember asm. - load to decking dolly		
Arm bushing & joint asm - install to crossmember	**N12**	**4**
Strut asm. - install into knuckle asm.	**N14**	**2**
Arm & ball joint asm.(lower) - asm. to knuckle		
Arm & ball joint asm.(lower) - secure	**N13**	**2**
F stabilizer bar - asm. bushings		
Stabilizer bar link - asm. to stabilizer bar	**N13**	**2**
Stabilizer bar - asm. to sub frame	**N10**	**4**
Link asm. - asm. to shock absorber	**N13**	**2**
F susp. & sub frame - deck & secure to vehicle	**N7**	**6**
	N8	**12**
F suspension strut - secure to body	**N11**	**4**

Station B: Instrument Panel Assembly and Installation

Operation Description	Torque Setting	Number of fasteners
IP asm. - select from shipping rack		
IP - load into sub-asm. fixture		
Cover asm. - sub-asm. to IP	**N02**	**2**
Cigar lighter opening cover - sub asm. to IP		
Ashtray lense - sub-asm. to ashtray housing		
Air bag diagnostic & backup power supply to IP	**N1**	**2**
Air bag diagnostic module to IP		
Plate cigar lighter - sub asm. to IP		
Utility tray - sub asm. to IP		
Insert finish panel lower - sub. asm to IP	**N02**	**2**
Pkg. tray panel vent - sub asm. to IP	**N02**	**2**
Cigar lighter ring & base - sub asm. to IP	**N02**	
Digital clock asm. - sub asm. to IP	**N02**	
Instrument cluster asm. - sub asm. to IP	**N02**	**4**
Warning light - sub asm. to IP		
Wiring clips - sub asm. to IP		
Wiring clip = sub asm. to IP brace		
Pipe clips - sub asm. to IP reinforcement		
Wiring channel - sub asm. to IP		
Wiring asm. (inst. cluster) - sub asm. to IP		
Inst. cluster glove compt. wiring branch		
Inst. cluster wiring loop - connect to inst. cluster		
Heater blower switch wire - connect to inst. cluster		
Clock & cigar lighter branch wires - connect		
Radio wire branch - through IP		
Heated back door window wire branch - through IP		
Driver's side wire branch & plugs - sub asm. to IP		
Heat control back window switch - sub asm. to IP		
IP asm. - asm. onto cowl top inner panel	**N2**	**10**
IP - asm. to cowl top inner panel brkt.	**N2**	**1**
Plug - asm. to IP	**N2**	
IP lower - asm. to heater	**N2**	**2**
Driver side lower panel - asm. to IP	**N03**	**6**
Fuse cover - asm. to IP		
Cover finish panel upper - asm. to IP		
Shroud cover - asm. onto upper steering column		

Appendix G Details of Workstation Comparisons

Summary of Nutrunners Used

The following table gives a summary of the ten tools used in the workstation comparisons in Chapter 7. The torque range and rpm for each tool were determined from literature from the nutrunner supplier. The cost of the FTNS tools is based on estimates from a representative of the supplier. Pneumatic costs are an average of the costs of eight pneumatic tools studied by Griffith [1992]

Tool	Torque Range	Est. Cost	Max. rpm
FTNS 1	N5 - N11	$ 4,500	910
FTNS 2	N10 - N16	$ 5,000	185
FTNS 3	N02 - N2	$ 4,000	1460
FTNS 4	N1 - N7	$ 4,000	680
Pneumatic 1	N7 - N8	$ 1,255	405
Pneumatic 2	N9	$ 1,255	400
Pneumatic 3	N10 - N12	$ 1,255	500
Pneumatic 4	N11 - N13	$ 1,255	400
Pneumatic 5	N14	$ 1,255	280
Pneumatic 6	N15 - N16	$ 1,255	180

Table G.1 Summary of Nutrunner Performance Data