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**Assessing the Performance of Automobile Body Assembly Equipment During Development and Production Stages**

by

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B.S., Mechanical Engineering  
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Submitted to the Department of Mechanical Engineering and the Sloan School of Management in partial fulfillment of the requirements for the Degrees of

Master of Science in Mechanical Engineering  
and  
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## **Abstract**

One critical element of the car-making process, which significantly effects quality, is the system that is used in the body shop to transform metal components into a vehicle. Body assembly tooling is so crucial because it tremendously impacts the structural integrity and quality of the vehicles being manufactured. If the body assembly equipment yields poorly constructed vehicles, this problem cannot be easily corrected downstream in the process. Additionally, because most body assembly systems don't have backup, or redundant systems, if part of the system goes down for an extended period of time, the lost production will almost immediately have a negative impact on the output of the entire body shop. Because the process of assembling automobile bodies is so critical, it is essential for automobile manufacturers to be able to thoroughly understand and evaluate how their body assembly equipment is performing.

Research was conducted at Chrysler Corporation to study the process of developing automobile body assembly equipment, to identify the factors which have the greatest influence on equipment performance, and to recommend strategies for optimizing equipment performance under high volume manufacturing conditions. Some of the factors examined include maintenance management and strategies, design methodologies and strategies, organizational structure, and equipment operating conditions.

This thesis focuses on the development and assessment of the body assembly equipment built to manufacture Chrysler's new NS minivan. Part I examines Chrysler's methodologies for building vehicles and developing automobile process equipment. Part II investigates several options for evaluating process equipment performance identifying applications and addressing the limitations. Some of the assessment techniques investigated include computer simulation, reliability analysis, and an analysis of maintenance requirements. A case study is presented to analyze one of the NS body assembly systems and to test some of the various assessment techniques presented in the thesis. Finally, the thesis concludes with key learnings about Chrysler's body assembly development process.

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## 1. Introduction

Competition in the automobile industry is becoming more intense every day. In the past, consumers viewed purchasing a well-made, high quality vehicle as a luxury. However, the buyer of today, who is much more demanding, is beginning to perceive quality as a basic requirement. Automobile manufacturers will have to meet a certain minimum level of quality to be able to merely compete in the marketplace. Companies who expect to excel will have to gain competitive advantages through a variety of novel techniques.

In automobile manufacturing, quality is determined by many factors. One critical element of the car-making process, which significantly effects quality, is the system that is used in the body shop to transform metal components into a vehicle. Body assembly tooling is so crucial because it tremendously impacts the structural integrity and quality of the vehicles being manufactured. If the body assembly equipment yields poorly constructed vehicles, this problem cannot be easily corrected downstream in the process. Additionally, because most body assembly systems don't have backup, or redundant systems, if part of the system goes down for an extended period of time, the lost production will almost immediately have a negative impact on the output of the entire body shop. Because the process of assembling automobile bodies is so critical, it is essential for automobile manufacturers to be able to thoroughly understand and evaluate how their body assembly equipment is performing.

The process of assessing equipment performance can be divided into two distinct stages:

1. assessing performance while equipment is in its development phase, and
2. assessing performance while equipment is in its operating phase, producing vehicles.

The first stage requires techniques and tools for evaluating how a system will perform while the system is still largely conceptual. For manufacturing systems that are so large and expensive, prototyping is rare, thereby increasing the reliance on computer models, reliability field data, and accumulated design and development knowledge. The second

stage requires a thorough understanding of how various components, machines, and subsystems interact with each other, as well as with other environmental factors, to produce a total system output under real operating conditions.

While assessing equipment performance is in itself a complicated process, the process is further complicated by the fact that in the American automobile industry, a significant amount of the development and manufacturing of body assembly equipment is outsourced. When outsourcing this technology development, it is important for companies to be capable of communicating intelligently and concisely with their suppliers, which entails being able to clearly define specifications that accurately reflect the companies' needs. These specifications must be understood explicitly before one can pursue, in a truly meaningful way, the task of evaluating systems and determining if the specifications were met. With unclear specifications, it becomes very difficult, if not impossible, to determine if the equipment is performing as it should.

Another difficulty with assessing equipment performance is the complexity and interdependence of the data that is collected from these systems. The tasks of deciphering data and accurately interpreting the results of the data are quite challenging, given that a myriad of factors, which cannot be easily isolated, impact the system performance. It is crucial to understand what factors in the system effect equipment performance so that these factors can be controlled in an attempt to optimize total system performance. However, a great number of these factors are hard to quantify, and/or control.

Research was conducted at Chrysler Corporation to study the process of developing automobile body assembly equipment, to identify the factors which have the greatest influence on equipment performance, and to recommend strategies for optimizing equipment performance under high volume manufacturing conditions. Some of the factors examined include maintenance management and strategies, design methodologies and strategies, organizational structure, and equipment operating conditions.



This thesis will characterize the automobile process equipment industry, focusing on American automobile manufacturers. A specific emphasis is placed on Chrysler's methodologies and practices for building cars, with a discussion of how organizational structure and culture effect Chrysler's strategies. A more detailed analysis will be presented regarding Chrysler's specific methodologies for designing, building, and evaluating body assembly equipment. Additionally, a discussion of how equipment reliability and maintainability is effected by maintenance strategies and early design decisions will be presented. Finally, the thesis will conclude with a set of key learnings and recommendations.

## **Part I: Manufacturing Automobiles and Developing Automobile Process Equipment**

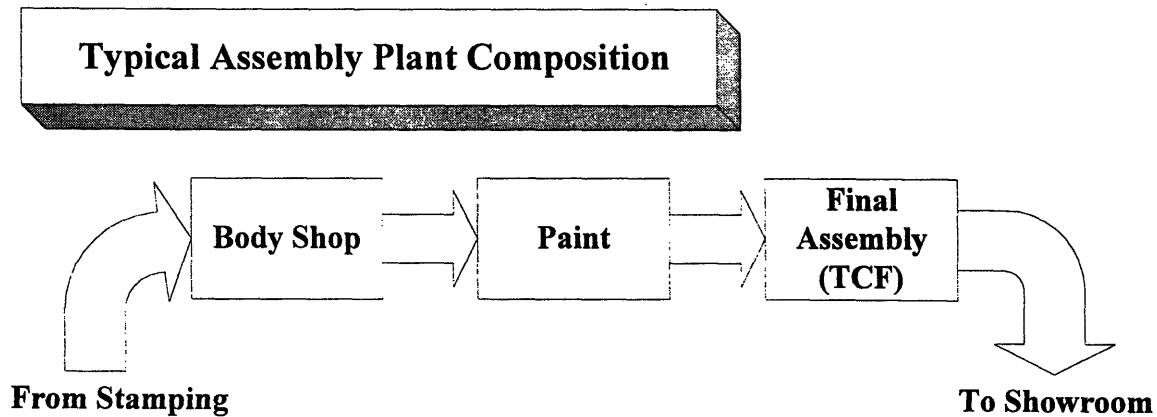
### **2. Methodologies for Making Vehicles**

#### **2.1 *Chrysler's Practices***

Chrysler is primarily organized according to product groups with a few centralized functional groups serving all the product (platform) teams. Members of the small car, large car, and minivan platform teams are located at the Chrysler Technology Center (CTC) which “integrates under one roof the product development function with the manufacturing process - and all the steps in between.” The product development effort begins with early simultaneous engineering activities driven by both product and process engineers. As the product decisions become somewhat firm, the specification and development of manufacturing systems begin to solidify. The manufacturing organization is largely responsible for ensuring that the vehicles can be made at a specified rate, within a certain time frame, and within certain quality specifications.

The manufacturing organization at Chrysler is divided into several major groups: advance manufacturing engineering, continuous improvement process, manufacturing planning and operations control, and power train, stamping, components, and assembly operations. The two groups that have the majority of the responsibility for developing body assembly systems are advance manufacturing engineering and assembly operations. The responsibilities of the advance manufacturing group include process design, equipment specification, and managing supplier relations. Each platform has its own advance manufacturing engineering group which resides in the Technology Center (except for the Jeep/truck platform that has a separate engineering center) with the platform teams. The assembly operations organization is comprised of all the assembly plants, and its members usually reside in the plants. An assembly plant, where various components are received and processed to create a vehicle, typically consists of a body shop (where stamped metal parts are welded together to form the body of the vehicle), a paint area, and a final assembly area (also referred to as trim, chassis, final - TCF), as

shown in Figure 1. This thesis focuses primarily on the body shops of the minivan assembly plants.



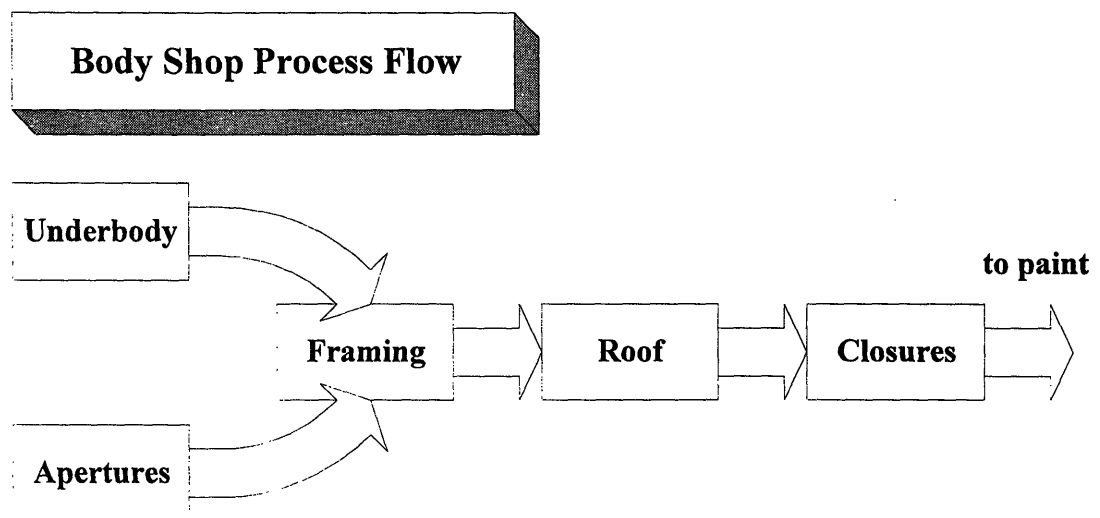
**Figure 1: Process Flow of an Automobile Assembly Plant**

At Chrysler, some products are dedicated to one assembly plant, others are assembled in multiple locations. While most assembly plants manufacture a single product, assuming that vehicles that are in the same family are considered to be one product, a few plants produce vehicles from different product families.

The assembly plants have a unionized hourly workforce consisting of production operators performing assembly tasks, and skilled trades people performing maintenance functions. The maintenance function is usually a separate entity from production, although in some plants the two groups may report to one manager. The assembly plants typically operate with a lean support staff.

The body shop, which consists of a series of large integrated automated welding systems, historically has been a large source of downtime in automobile assembly plants. Many of the welding systems have maintenance personnel assigned to them whose responsibilities entail repairing the system when it malfunctions or breaks down. However, maintenance

workers sometimes spend a significant amount of time watching the control panels, waiting for problems to arise. The major body shop systems include underbody, apertures (body sides), framing, roof, and closures (doors, hoods, lift gates, etc.) as depicted in Figure 2. The underbody systems weld parts together to build up the floor of the vehicle. The aperture systems weld parts that form the sides of the vehicle. The underbody and apertures are then married at the framing system where the two apertures are attached to the underbody. Once the vehicle is framed, the roof is attached, followed by the addition of the closures. Finally, the welded vehicle, with closures, is shipped to the paint area. After the vehicle is painted, it is sent to the final assembly area where components and trim accessories are added (e.g. engine, windshield, seats, carpet, etc.).



**Figure 2: Process Flow of a Body Shop in an Automobile Assembly Plant**

Chrysler has two North American minivan assembly plants. The current model minivan (AS) has been in production since 1984 without any major product design changes. Chrysler's introduction of the 1996 model year NS minivan in mid-1995 will be the first ground up redesign of the minivan since Chrysler introduced the minivan concept over 10 years ago. Because the NS is a completely new product, and body assembly tooling is

typically product specific, a whole new set of body assembly tooling systems will be used to manufacture the new minivan.

Towards the end of the AS life, both plants were operating three shifts per day. Some of the process equipment was about 10 - 12 years old, some was newer, but the actual technology employed may have been much older. The AS body assembly systems contain a great deal of hard tooling and hydraulic systems. Design for maintainability was not given much consideration when the AS body systems were originally developed. This equipment is hard to maintain because many components of the system are difficult, if not impossible, to access. Many of those familiar with AS operations point to lack of time (because of three shift operations) and biases against PM (because of failed programs of the past) as the primary reasons for not further developing the current maintenance program.

With the introduction of the NS, one plant will initially operate for two shifts per day and the other for three. The plants will be receiving two sets of practically identical equipment, but since the minivan production launches are staggered, the two sets of equipment are primarily built sequentially, not simultaneously. The NS body assembly equipment primarily consists of robotic welding systems with some manual welding stations and some hard tooled welding stations. There are at least three brands of robots, some of them reconditioned. Equipment manufacturers develop maintenance and operating manuals which includes specifying recommended PM tasks. Skilled trades people were involved with developing PM guidelines and provided early input with regards to improving equipment accessibility and maintainability. Additionally, the NS maintenance organization will utilize a computerized maintenance management system (CMMS) to help schedule maintenance activities.

### **3. Body Assembly Tooling Strategies**

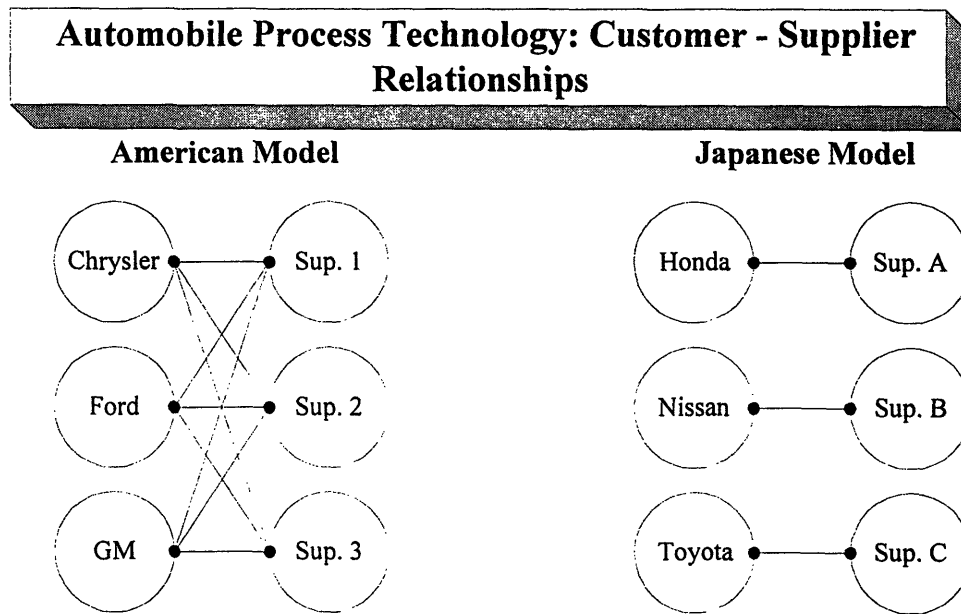
#### **3.1 Industry Practices**

Automobile manufacturers follow a variety of strategies and practices for developing manufacturing process equipment and technology. Ordinarily, the primary decision factors for designing the strategies are related to whether or not a company should develop the capabilities to design and build this technology internally or externally. In the American automobile industry, primarily three dominant strategies are pursued.

1. design internally and build internally
2. design internally and build externally
3. design externally and build externally

While these strategies can be grouped into three broad categories, it should be noted that most companies employ these strategies in varying degrees and the strategies typically evolve and shift over time. Although Chrysler has some internal capabilities to design and build a limited amount of automobile process tooling, the overriding strategy used for body assembly tooling at Chrysler falls into the third category of designing and building externally. Chrysler's tooling strategy can be summarized as a system of outsourcing the development of body assembly systems using multiple tooling philosophies that vary by platform. Ford can be described as pursuing a strategy of standardization of process technology, outsourcing much of the development process. GM, the most integrated American automobile manufacturer, pursues a strategy of developing its own internal technology development capability, especially for "advanced technology," while it outsources "commodity" systems using a competitive bidding scheme to a large extent. Honda, which views process development capability as a competitive advantage, develops and builds practically all of its manufacturing technology internally. While Toyota relies heavily on its extensive keiretsu structure for developing and building body assembly tooling, it does maintain this capability internally with a "significant internal manufacturing engineering organization." (Fine, Joglekar, and Parker, 1994; Chrysler, DCT, and PICO, 1994)

When companies choose to design and build process equipment externally, the relationships that emerge between an automobile manufacturer and its suppliers of body assembly process technology are extremely critical. Historically, American automobile manufacturers have promoted competition among their suppliers using competitive bidding practices. Recently, the trend has been towards building more long term partnerships with a core group of select suppliers. One hypothesis, illustrated in Figure 3, describes the U.S. model as a core group of process suppliers that works with all of the American automobile manufacturers. On the other hand, the Japanese model, also shown in Figure 3, seems to consist of a different group of core suppliers for each major automobile manufacturer, perhaps with some overlap. (Fine, 1995)



(From Fine Lecture, 1995)

**Figure 3: Customer - Supplier Relationships for Developing Automobile Process Technology**

Because of the trust and commitment developed in long term partnering relationships, suppliers are more likely to take more risks and incur more of the cost associated with developing body assembly tooling. Repetitive transactions that occur between

organizations can become less costly because of the time savings and efficiency gains attributed to establishing some level of familiarity. Also, the partnering shortens the time it takes for the customer to receive the end product because suppliers are willing to be early participants in the development process before all the details are worked out or before an official purchase order is received. For example, Chrysler's suppliers get involved with simultaneous engineering efforts to work on process design before the product design is finalized. Contrarily, GM's suppliers wait to receive purchase orders before they commit significant resources to a development project because GM still practices a large amount of competitive bidding.

### ***3.2 Chrysler's Relationship with Equipment Manufacturers***

Early in the product development stages for a particular vehicle, Chrysler's manufacturing organization becomes involved with preliminary process development activities. These preliminary activities are a part of a large simultaneous engineering effort that also consists of involving tooling manufacturers before any product decisions are finalized. In the past, Chrysler process engineers submitted detailed process and tooling specifications to equipment suppliers, utilizing the suppliers primarily to build body shop systems. However, the current trend has Chrysler demanding an increasing amount of engineering responsibility from its equipment manufacturers. In the area of body process assembly equipment, Chrysler has established a close working relationship with a few key suppliers of major body shop systems that include Detroit Center Tool (DCT) and Progressive Tool and Industries Co. (PICO).

Instead of the over-the-wall approach to the design and build of body shop systems of the past, the current relationship between customer and supplier promotes long term shared learning and responsibility. Both parties work to solve problems jointly while building a lasting relationship. In addition to suppliers being involved early during simultaneous engineering activities, Chrysler engineers are located on site with the suppliers during the equipment build phase. One of the major objectives of this cooperative relationship is to



try to create a system of open data and information sharing between suppliers and plants. Another objective is to capitalize on DCT's and PICO's strengths as systems integrators. While DCT and PICO build some components internally, their true core competence lies in the ability to successfully integrate a large set of complex equipment.

While this system seems to have many advantages for Chrysler, the manufacturers feel as if they are working with several different companies when interacting with the various platform teams and/or plants. This sentiment can be attributed to the fact that Chrysler has no common tooling philosophies across platforms. Because Chrysler is organized around products, the equipment manufacturers work with a different group of people for each body shop equipment project. Since there is no common process philosophy that is shared throughout the corporation, each platform team makes its own decisions, acting in many ways like independent companies. Ford has been described as following a standard process for designing and building body assembly systems. Chrysler, on the other hand, may have six different approaches to developing body assembly systems.

In the past, Chrysler sought competitive bids on tooling projects from many different suppliers. The competitive bidding process required that Chrysler take on a great deal of the design and engineering work since a tremendous amount of detail and specification was needed by suppliers so that they could bid on projects. Chrysler being the least vertically integrated American auto manufacturer, currently does not have the infrastructure to support designing and building body assembly tooling internally, thereby increasing its reliance on equipment suppliers to perform more functions. As the nature of Chrysler's relationships with process technology suppliers has changed, Chrysler has become less involved with the detailed specifications of the systems, relying more on the suppliers to provide engineering and system integration services. However a new skill set is required to successfully manage supplier relationships. According to Dan Whitney (1995) the essential skills in outsourcing are 1) defining competent specifications, 2) finding competent sources, and 3) determining that the specifications were met. Additionally, since major systems are not all designed and built by a single supplier, the

competitive atmosphere amongst suppliers has changed. The integration of the complex body assembly systems being built by multiple suppliers requires a tremendous amount of coordination and cooperation among the various suppliers.

Chrysler is reaping an abundance of benefits from the long term partnerships that it is developing with some of its suppliers. Because of the increased sense of commitment from Chrysler that is felt by the suppliers, the suppliers are more willing to incur more risk and assume more engineering and technology development responsibility. For a supplier who has several customers building long term partnerships, it becomes less expensive to invest and develop new process technologies because the costs can be shared among the supplier and all its customers. Another advantage of this system for Chrysler is that since its various supplier partners have to integrate the assembly systems, it becomes necessary that the suppliers work together cooperatively, unlike the competitive rivalries of the past, which will increase the total knowledge pool available to Chrysler and its suppliers. Because the supplier base works together, learning can be shared to improve the overall performance of any one supplier. Also, because the suppliers become familiar with Chrysler's infrastructure and practices, the entire development process can be expedited. One ancillary benefit for Chrysler is the ability to get a glimpse of what the competition is doing, but on the other hand, the competition also gets a peek at what Chrysler is doing.

Though these new relationships between customer and suppliers provide many benefits not available with the previous relationships, there are several distinct disadvantages that accompany the long term partnering relationships. One notable disadvantage of these relationships is that since the supplier companies provide services for a variety of automobile manufacturers, no one auto maker can easily gain competitive advantages through technology innovation because they all have access to the same technology. Additionally, Chrysler faces the possibility of losing expertise in developing assembly process technology. While Chrysler may not need a whole organization of process technology experts, relying too heavily on suppliers to provide this expertise puts

Chrysler in a very vulnerable position. Although Chrysler is moving toward long term relationships with suppliers, the independent interactions of each platform with equipment manufacturers limits the total advantages to be gained.

As Chrysler continues to develop and nourish its relationships with process equipment suppliers, it will have to attempt to continually improve interaction with suppliers, particularly in the area of communicating needs and specifications. To be truly effective, Chrysler also needs to create a sense of total ownership among suppliers. Currently, individual suppliers feel like they are not responsible for the performance of the entire body shop. In the truest sense, they perhaps are only responsible for the systems they develop and build, but if they are trying to develop an effective partnering relationship with Chrysler, that attitude must change. The suppliers need to be concerned with total system performance, not just their respective parts of the system. Achieving this level of commitment and concern for any one supplier entails working very closely and cooperatively with other suppliers.

One of the problems that needs to be addressed in order to achieve a sense of supplier ownership is the lack of well defined and well understood guidelines. Chrysler doesn't provide a rigid structure or stringent guidelines for the suppliers with regards to total system optimization, thereby giving the equipment manufacturers a greater degree of flexibility and latitude. More rigidity and better communication may be needed to address the issues of system optimization and enhancing equipment performance. Everyone involved throughout the process development process has to be in synch in order to develop the best possible system that meets Chrysler needs. Therefore, Chrysler will have to lead the way to forming more cooperative relationships among its suppliers by enhancing communication and developing joint goals and objectives.

## **4. Designing Automobile Assembly Equipment**

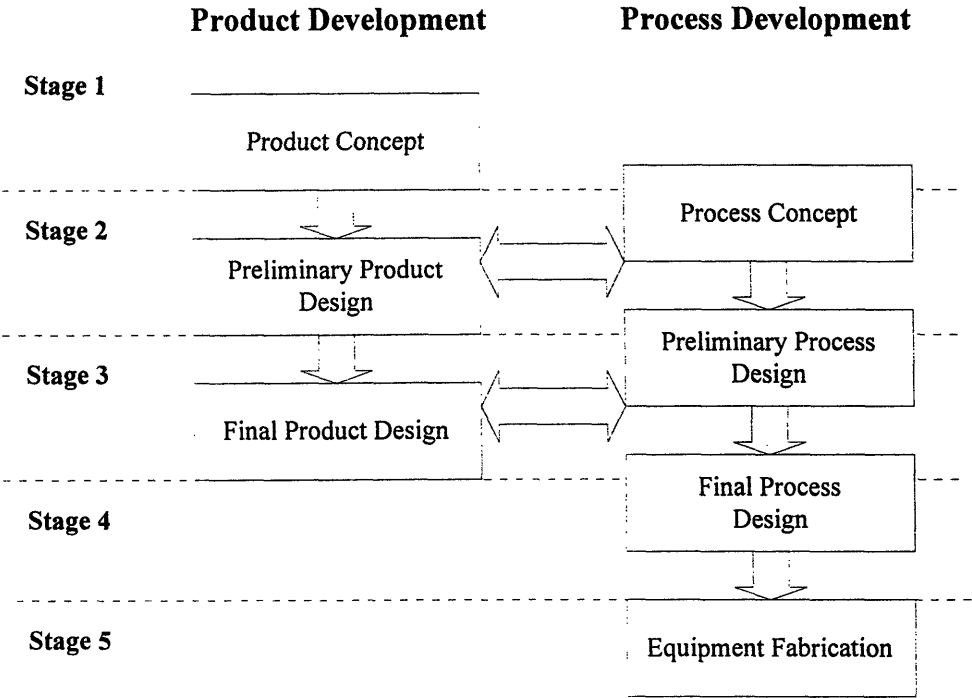
### ***4.1 The Process of Developing Body Assembly Systems***

Designing manufacturing processes for building automobiles is a very challenging and complicated task, which consists of two main components: 1) specifying manufacturing processes and 2) designing equipment to complete the specified functions. The most effective design practices involve process and equipment designers during the early stages of product development. Although very little detailed process design can occur before the product design becomes somewhat rigid, the early involvement of the manufacturing organization allows for product and process issues to be addressed simultaneously, which has proven to be very beneficial.

For new vehicle development programs at Chrysler, simultaneous engineering efforts are pursued for product and process design. Because of the long term partnerships with the process equipment suppliers, the suppliers become involved during the early stages of the process development activities. Process engineers, plant personnel, and suppliers work closely together to set objectives for process equipment and to develop ideas and concepts for accomplishing the objectives. Several proposals are created representing various methods for accomplishing the stated goals. For example, body shop design proposals might include information such as the physical layout for an assembly line, methods for welding parts, and methods for loading and unloading parts.

Product and process development activities can be separated into several major stages as depicted in Figure 4. During the first stage, the vehicle is still largely in conceptual form. During this stage, the manufacturing and process groups become involved, planning and thinking conceptually about various methods for manufacturing the vehicle. However, as the process moves into the second stage, some of the product choices begin to become firm as preliminary design decisions are made. Preliminary process decisions are considered as well with product and process decisions being made iteratively. As the vehicle approaches the final product design phase (Stage 3), the process group works with

the equipment manufacturers to create more concrete process and equipment designs, again working iteratively with the product group. Once the product design has been approved and the development process enters into Stage 4, the final process and equipment decisions are made. Finally, after some degree of validation of the proposed systems, the systems are fabricated by the equipment manufacturers.



**Figure 4: A Typical Process for Designing Products and Processes at Chrysler**

In order to make process design decisions, various options are weighed considering factors such as cost, flexibility, safety, space requirements, and ergonomics. In general, American automobile manufacturers are quite conservative when it comes to introducing new, cutting edge process technology into their factories. (Chrysler, DCT and PICO, 1994) The strategy that prevails for choosing which type of technology to incorporate into new body assembly systems tends to be one which consists of achieving moderate improvements. That is, rather than choosing a new, riskier technology which could

potentially leap frog the current systems being used, most companies tend to choose the safer, more proven technologies.

## **4.2 The Process of Validating Body Assembly Systems**

### **4.2.1 Challenges of Validating Body Assembly Systems**

One of the biggest challenges with designing and building body assembly tooling is accurately assessing and validating equipment performance during the design stages.

Throughout the majority of the process development activities, the processes and equipment exist first, merely as concepts, and later as more detailed engineering drawings. The scale and complexity of most body assembly systems are not conducive to pre-fabrication prototyping. Not being able to build prototype systems probably contributes to automobile manufacturers' reluctance to incorporate new technology into their systems. Even if prototyping were feasible and more widespread, another problem surfaces because some system weaknesses still will not be exposed until the equipment is actually used under high volume manufacturing conditions. Therefore, a great deal of troubleshooting occurs only after a vehicle production launch begins, the time when the auto makers want to experience the fewest problems.

Another major contributing factor to the difficulty of evaluating and validating automobile process equipment is the lack of standard measures and definitions. While there have been recent attempts at developing tools and standards related to assessing equipment performance for the automobile industry (one such effort is the creation of the book entitled *Reliability and Maintainability Guideline for Manufacturing Machinery and Equipment* by the big three American car manufacturers, several equipment supply companies, other industrial companies, and universities), these tools have not yet been disseminated on a large enough scale to be highly effective.

There still exists a great deal of ambiguity and confusion in the discussions between Chrysler and its process equipment suppliers about the many dimensions of equipment

performance. For example, one major issue that was hotly debated during the NS process development program is related to defining, measuring, and achieving 95% uptime goals. Much of the ambiguity lies in the absence of a standard, mutually agreed upon understanding of what Chrysler really expects in terms of performance of its manufacturing process equipment. One such case is seen in the use of the term uptime, which can be interpreted to mean many things depending on what type of assumptions are made. To eliminate the ambiguity, Chrysler will have to work jointly with its suppliers to determine and explicitly specify its requirements for equipment performance. Only then will it be appropriate to select or develop a metric that accurately assesses the degree to which equipment manufacturers meet Chrysler's requirements.

#### **4.2.2 The Role of Computer Simulation in Equipment Assessment**

One means by which equipment manufacturers and buyers attempt to understand system performance for process equipment is through the use of computer simulation techniques. Because it is extremely expensive to try to simulate actual production conditions using real equipment and parts, many have come to rely on computer simulation methods for evaluating system performance before the equipment is able to be run under high volume production conditions.

##### ***4.2.2.1 Limitations of Computer Simulation Techniques***

Although there is a tremendous reliance on computer simulation data and historical information for use during validation processes, these methods typically yield inaccurate results. Because the systems are so complex and affected by a myriad of factors, it is nearly impossible to model the systems so that they accurately predict the behavior and performance of the system. Also, many of the conditions affecting equipment performance cannot easily be modeled. In addition, the results of computer simulation models are only as good as the data and information used as input for the models. Although computer simulation may not be totally accurate, the accuracy and usefulness of the results can be drastically improved with the use of good data. Knowing the

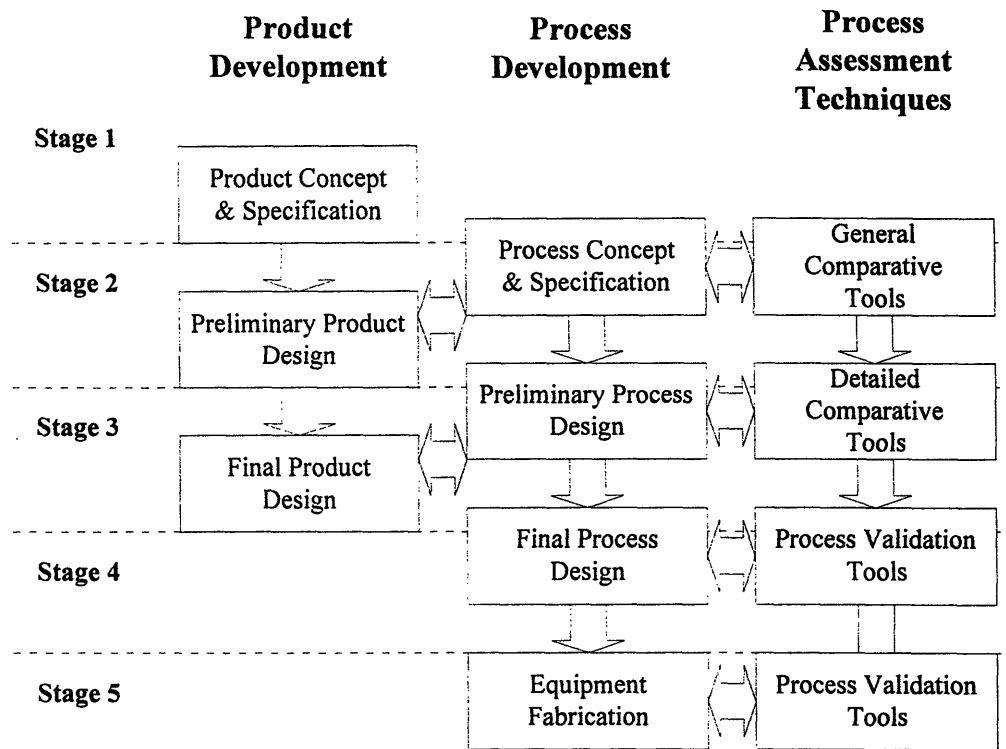
limitations of computer simulation can enable a development team to intelligently apply simulation and validation techniques throughout the process of designing process development equipment.

#### ***4.2.2.2 Applications for Computer Simulation Techniques***

When computer simulation models cannot accurately predict equipment performance, the biggest benefit can be gained by applying these models, very early in the equipment development cycle, as comparative analysis tools (see Figure 5). During Stage 2 of the product-process development cycle, when initial process concepts are proposed, the team members should compare the various design options by analyzing the total system and focusing on the subsystem interactions and the subsystem requirements necessary to achieve the established goals. During Stage 3, a more detailed simulation model can be built using more specific knowledge about equipment options. The focus should be on determining the necessary equipment requirements for achieving system performance goals, using the simulation process to compare various options and identify those options which seem to be the most suitable candidates for achieving equipment performance goals.

Understanding the strengths and weaknesses of computer simulation is necessary for maximizing its value during the development process. Given that the results are sensitive to the input data and that all conditions cannot be modeled, simulation should not be utilized as a validation tool after the designs have been frozen or after the equipment has been built. Instead, it should be used as a comparison tool for optimizing system design and layout. Used early in the process development stages, computer simulation can be a worthwhile tool for comparing proposed system designs. Given that all factors cannot be incorporated into the model, developing a base model and comparing various design options will allow one to observe and analyze the relative effects on system performance. Any simulation models that are used to generate absolute system performance measures have to be considered with extreme caution.





**Figure 5: Applications for Process Assessment Tools During Process Development**

#### 4.2.3 The Role of Reliability and Maintainability (R&M) in Equipment Assessment

To supplement the use of computer simulation techniques, as well as provide solid input data for simulation models, it is important to understand two very key aspects of equipment performance 1) equipment reliability, and 2) equipment maintainability. While these two factors are quite critical, they are very hard to define, quantify, and measure in relevant and practical ways, especially during early stages of process development.

S. S. Rao (1992) provides two concise definitions for reliability and maintainability.

*Reliability* is the probability of a device performing its function over a specified period of time and under specified operating conditions. *Maintainability* is defined as the probability of repairing a failed component or system in a specified period of time.

Another useful indicator of equipment performance is equipment availability, which encompasses both reliability and maintainability. The term *availability* is used to indicate the probability of a system or equipment being in operating condition at any time  $t$ , given that it was in operating condition at  $t = 0$ . (Rao, 1992) While the definitions may seem straightforward, the process of translating the definitions into practical evaluation and measurement techniques is rather intricate. Many of the nuances associated with transforming theoretical models into practical application tools are not well understood.

#### ***4.2.3.1 Limitations of Reliability Assessment Tools***

One of the major stumbling blocks to achieving meaningful results about equipment performance from reliability analyses, is the lack of supporting data to build accurate models and make valid assumptions. Many assumptions and simplifications must be made in order to get any use from the theoretical reliability and maintainability concepts, and often these assumptions are nothing more than best guesses or gross approximations. Another problem with applying reliability analysis during the process equipment development cycle is the difficulty of simulating actual production conditions and acquiring reliability data before the equipment has been installed and ramped up to its steady state operating level. The validity of reliability data gathered outside of the normal operating conditions is questionable because small environmental changes can have a significant effect on equipment reliability.

#### ***4.2.3.2 Applications for R&M Tools***

Although there are some deficiencies associated with employing reliability and maintainability tools during the development stages of process assembly equipment, there are many benefits to be reaped if these analytical tools are used properly. Two of the biggest benefits to be gained are expressed by Davidson (1988):

Plant designers and manufacturers have become aware that reliability assessment can help to demonstrate which of several likely alternative design schemes is likely to meet a specified reliability requirement most economically. Conversely, reliability assessment can also demonstrate

which parts of a design scheme are not critical to reliability performance and therefore, can be made to less stringent requirements without compromising overall reliability and safety.

On the other hand, one should not necessarily expect to achieve highly accurate results from R&M analysis, therefore sensitivity analysis is useful for understanding the limitations of the results. In addition, Davidson (1988) suggests that in order to properly apply reliability analysis tools to systems, it is critical to know three things:

1. interactions of sub-sections of the system
2. something about the failure rates of the sub-sections, and
3. something about the repair rates of the sub-sections.

The most important thing to remember when applying these tools early in the design process is that they are merely estimates and should serve only as guidelines, and similarly to the computer simulation tools, reliability and maintainability tools are best utilized as comparative tools during the process development cycle, rather than a means to calculate or predict some exact measure of system performance.

#### **4.2.4 System Testing and Validation During Body Assembly System Development**

There exists a great number of practical approaches that can be utilized for assessing, testing, and validating process systems during development stages. The following section will examine some recommended test procedures borrowed from product design processes and review several techniques for assessing equipment performance during development stages.

A. D. S. Carter (1986) describes four categories of testing that should be considered when designing for reliability:

1. full scale testing under real conditions
2. full scale testing under simulated conditions
3. full scale component testing
4. detailed rig testing.

Though Carter focuses on reliability in product design, many of the principles are still applicable for process design. Full scale testing under real conditions, Category 1, is a desirable, but often unattainable, objective for large process assembly systems. Not only is this category of testing prohibitively expensive for body assembly system design, but real conditions frequently are not available and are nearly impossible to control. Similarly, Category 2 is often impractical for large process systems, but may be a viable alternative for smaller design projects. Full scale testing under simulated conditions is also an expensive technique, but unlike the methods in Category 1, the conditions can be more carefully controlled. Nevertheless, there inevitably will be some unforeseen real operating conditions that cannot be simulated. The last two categories probably have more practical applications for body assembly system design. Category 3, full scale component testing, is advantageous because comprehensive testing can occur on critical components which can be conducted early in the development stage without incurring a huge cost. Finally, the fourth category involves analyzing a small part of the system in a special test rig in order to gain a fundamental understanding of how the equipment is operating.

In addition to the four general categories of testing suggested by Carter, many specific options exist for evaluating design alternatives during development processes. Some of the options are equally applicable for both product and process design. The remainder of this discussion will focus on applications of assessment techniques for large process assembly systems. Some of the specific tools which are useful include: reliability diagrams, failure modes and effects analysis, fault tree analysis, computer simulation models, maintenance composition, and preventive maintenance requirements. As shown in Figure 5, these process assessment techniques can be applied effectively at various stages of the process development cycle.

During Stage 2, it is beneficial to use general process assessment tools as specifications and ideas are being generated, to compare the various ideas. As the process designs begin to take more form in Stage 3, more detailed process assessment tools are required. Again,

these tools should be used for purposes of comparison rather than as a means of estimating absolute equipment performance measures. As Stage 4 begins, and more decisions are made regarding equipment design selections, process validation tools are needed that can begin to verify that proposed systems are indeed capable of meeting specified goals. And finally, during Stage 5 as the designs begin to become physical systems, process validation tools are needed that work well for evaluating physical systems that are not yet functioning under real operating conditions.

During design stages, two useful tools are design reviews and failure modes and effects analysis (FMEA). Design reviews should occur to evaluate proposed designs for compliance with the specified requirements. To be effective, the design review should occur frequently and thoroughly. Issues regarding R&M should be addressed as early as possible, because R&M levels are largely determined by the initial design decisions that are made. Some of the requirements and issues that should be addressed include manufacturability, reliability, maintainability, PM (and other planned maintenance) requirements, etc. Those participating in the design review should devote a significant amount of time to comparing the options based on how each option meets the stated objectives and requirements with regards to equipment reliability and maintainability. FMEA should also be conducted during the early process design stages, in order to identify various failure modes and analyze their effects on system reliability. On an equipment level, the FMEA should address the R&M of each machine, while the FMEA on a process level should address the integration of machines into the process.

During build and install phase, some useful techniques include systematically collecting data, recording corrective action, developing a failure reporting system, and identifying pattern failures. During the equipment build and install phase, it is essential that data collection and corrective action records are accurately maintained. Some of the key data to track includes, operating time, equipment failures, and completion of PM tasks. It is also crucial to establish predictive maintenance baselines such as vibration signatures or thermal fingerprints, so that predictive and condition monitoring techniques can be

employed throughout the life of the equipment as a significant part of ongoing R&M analysis. To facilitate this ongoing R&M analysis, a failure reporting system needs to be designed that begins with the supplier, while the equipment is being designed and built, and continues once the equipment has been installed and is operating in the plant. Putting such a system in place will enable recurring failures to be systematically detected and corrected. In order to get the most out of R&M analysis, an approach broader than the more narrowly focused traditional approaches needs to be pursued. For example, rather than simply focusing on collecting numerical data to determine the failure rate or the mean time to failure, it will be more important to gather information that tells when, where, why, and how a particular failure occurred.

## **Part II: Evaluating Process Equipment Performance**

### **5. Maintenance Assessment**

Equipment maintenance is an issue that traditionally has not been a high priority in many manufacturing companies. As competitive forces intensify, optimizing equipment performance has emerged as one of the key concerns of manufacturing managers.

Companies are beginning to realize the significant impact that maintenance policies and practices can have on equipment performance, cost, and quality. Nevertheless, there is wide spectrum of maintenance strategies that companies pursue, some very reactive and others quite proactive. The purpose of this maintenance assessment is to 1) compare various maintenance policies, focusing on those at Chrysler, 2) summarize some of the key learnings about maintenance, and 3) review and evaluate some components of the proposed NS preventive maintenance program.

#### **5.1 Maintenance Policies**

##### **5.1.1 Run-to-Failure Maintenance**

Run-to-failure maintenance (RTFM) is a reactive maintenance policy where repair, adjustments, and replacement are done only after equipment has failed. This type of maintenance strategy is commonplace in many assembly plants. RTFM fits in well with the “fire fighting” mode of operation, seen in many high volume manufacturing facilities, where workers and managers consistently encounter crises which need immediate attention.

Following this type of maintenance practice can be very problematic and expensive in an environment where equipment downtime is costly. RTFM results in a large percentage of unplanned maintenance, which in turn leads to an inefficient allocation and utilization of maintenance resources. Another evil associated with RTFM is the high levels of spare parts inventory that must be kept on hand so that the maintenance department can be prepared to repair a failed machine as quickly as possible.

Although RTFM can be very costly when used as the primary means of maintaining equipment, in some cases, it makes sense to adopt such a strategy for equipment. For example, if maintenance resources (time and people) are very limited, it may make sense to employ a RTFM strategy on non-critical equipment that does not directly or immediately impact production.

### **5.1.2 Preventive Maintenance**

Preventive maintenance activities include regularly scheduled inspection, adjustment, cleaning, lubrication, parts replacement, calibration, and minor repair of equipment. PM plans are usually time or interval based and give no regard to the actual condition of the equipment. The intervals for PM activities are based typically on failure rates. Two assumptions underlie a preventive maintenance strategy:

- equipment wears over time, and
- overhaul and parts replacement will improve the condition of equipment restoring it to like new condition (i.e. there are no harmful effects from replacement and overhaul)

The biggest benefits gained from PM come when it is used on equipment and/or components that exhibit wearout characteristics. Donald Morton (1994), in a recent article in *AIPE Facilities*, points to a Department of Defense study of the U.S. aircraft industry which argues that “only 6% of all equipment exhibit wearout characteristics.” Furthermore, he states that equipment falling into this category is “typical of single-piece and simple items such as tires, compressor blades, brake pads, and structural members.” Since most complex items exhibit failure characteristics other than wearout, it becomes almost impossible to accurately predict when these type of components or systems may fail. Without an accurate prediction of equipment failure, PM intervals cannot be precisely nor wisely set, as evidenced by the belief by many in the auto assembly plants that equipment manufacturers are recommending PM schedules that are much too conservative. This practice of “arbitrarily” assigning maintenance intervals is very costly



and inefficient. Therefore, in order to gain the full benefits of a PM program it should be included as a part of a broader maintenance strategy and should be relegated to that equipment which indeed exhibits wearout failure characteristics.

At Chrysler, for the NS program, PM procedures were developed jointly by reliability and maintenance personnel from the equipment manufacturers and skilled trades workers from both assembly plants. The bulk of the responsibility for developing the procedures fell upon the reliability and maintenance organization at the supplier companies, which received significant input from plant representatives. The detailed procedures contained information about frequency, time to complete task, work classification, and scheduling opportunities. These tasks were developed based upon past experiences of the skilled trades people, limited failure data collected from the field, and limited failure data from robot and other component manufacturers.

### **5.1.3 Predictive Maintenance**

Predictive maintenance (PdM) uses condition monitoring techniques to assess equipment condition and predict equipment failures. Pursuing a PdM strategy allows corrective action to occur before equipment fails. Some example of PdM techniques include vibration analysis, thermography, ultrasonics, and particle analysis. Some companies are beginning to invest in predictive maintenance technologies with the “expectation of improving equipment reliability and availability while lowering maintenance costs.”

(Murry and Mitchell, 1994)

According to Murry and Mitchell (1994), the benefits of an effective PdM program are numerous. Some of the benefits to be gained include:

- early detection on incipient problems
- decreased maintenance costs
- reduced corrective maintenance effort
- optimized overhaul cycles

- minimized probability of catastrophic failures
- extended equipment life cycles
- optimized preventive maintenance
- increased equipment readiness

At Chrysler, PdM policies are surfacing in a very localized manner in some of the assembly plants. However, there does not seem to be a widespread commitment to developing comprehensive PdM programs thus far. Traditionally, there has been a large reliance on PM and RTFM policies, but as many of the plants begin to operate for three shifts each day or run a significant amount of overtime, the time allotted for PM vanishes and RTFM becomes too costly. With very limited time and personnel resources, Chrysler will be able to reap huge benefits by implementing some basic PdM techniques. While some predictive techniques can be very costly or require extensive training, a cost analysis is likely to show that many of the services are indeed justified.

#### **5.1.4 Developing a Maintenance Strategy**

Companies with the most effective maintenance organizations and programs share some common practices. One of the most important factors contributing to the success of maintenance programs lies in the ability of companies and organizations to thoroughly understand the costs and benefits of various maintenance activities. Another important element is the presence of a sense of shared responsibilities, at all levels of the manufacturing organization, for accomplishing maintenance objectives. In addition, companies with highly regarded, successful maintenance functions are capable of planning and carefully choosing which maintenance strategies to pursue. Other factors contributing to the success of maintenance functions include integrating maintenance and production organizations, establishing a maintenance feedback loop to facilitate moving down the operating learning curve, and developing cooperative relationships with equipment manufacturers.

In order to develop the most effective maintenance strategy for the future, Chrysler will have to capitalize on the strengths and address the weaknesses of its current maintenance management system. One of the biggest assets that must be utilized to its fullest potential is the workforce. The maintenance personnel who work with the equipment on a daily basis are extremely knowledgeable and usually have a very good understanding of the idiosyncrasies of the equipment. Also, the recent trends in Chrysler's supplier relationships have created many newfound cooperative partnerships among customer and supplier. Chrysler has to take full advantage of the various resources, skills and knowledge, that suppliers are willing to share. This type of relationship led to a joint development of preventive maintenance tasks by supplier reliability and maintenance personnel and assembly plant skilled trades workers for the NS body assembly equipment. These type of cooperative efforts will lead to better results for all parties involved. The suppliers will have access to failure and repair data which will help them improve future designs. As more data is collected about equipment performance, Chrysler will be able to enhance its own maintenance programs, and eliminate recurring equipment problems.

Some weakness have to be overcome as well. Currently, maintenance has a lower priority in the manufacturing organization than production. As long as maintenance is viewed as a less important activity than production, it will be very difficult to develop and implement a truly comprehensive maintenance strategy. Also, in order to justify some of the expense associated with expanding or upgrading a maintenance program, the costs must be well understood, including costs which are not so obvious, such as the cost of lost production, the cost of lost customers because of quality problems, the cost of shortened equipment life, inventory costs for carrying excessive spare parts, etc. The final area for improvement is related to developing and disseminating a maintenance strategy. The strategy should be well defined and explicitly stated so that everyone can understand the role and importance of maintenance activities.

## **5.2 Key Learnings about Maintenance**

The following section discusses some of the key learnings regarding maintenance in general, with an emphasis on preventive maintenance. These learnings come from a variety of sources which include industry literature, academic literature, benchmarking studies, observation, and interviews. Several articles and books about maintenance management (for example Voigt, 1994 and Nakajima, 1988) stress the importance of building a supportive organization to help implement various maintenance strategies. Others focus on the cost associate with various maintenance practices (for example Murry and Mitchell, 1994). Field observations and benchmarking studies at several Chrysler plants demonstrates the effects of various maintenance programs and strategies in practice.

- **For a successful PM program, top plant management must demonstrate through actions, not just words, commitment to PM.** This is evidenced within Chrysler by the successful efforts at the Belvidere assembly plant with regards to developing and implementing various aspects of a PM program. Although the PM program there has not yet been perfected, many accomplishments have been made thus far, largely due to the tremendous amount of unwavering support given by the plant manager.
- **Having dedicated PM coordinators and work crews helps to ensure that the program is followed.** The experience at Belvidere demonstrated that it is much more difficult, in the current operating environment, to successfully complete many PM activities without dedicated crews because maintenance personnel tend to get pulled away from PM activities to perform more “urgent” tasks.
- **To increase the likelihood of a successful PM program, involvement and support at all levels of the organization are necessary.** Management’s commitment to the maintenance strategy must be visible to all. (Voigt, 1994) Additionally, everyone in the organization must clearly understand how their job relates to the overall maintenance strategy and program in order to maximize their level of involvement.

Any individual or group that is not fully committed or involved could easily undermine the effectiveness of a maintenance program. Gaining the necessary level of support and involvement will require a tremendous amount of training and education is necessary to eliminate the negative biases against PM and other maintenance programs.

- **The costs and benefits of maintenance policies need to be thoroughly understood in order to make informed decisions about maintenance strategies.** In order to support such an analysis, data needs to be diligently collected in order to develop maintenance cost models as well as to assess equipment maintainability and increase the accuracy and usefulness of reliability analysis. Understanding both cost information and equipment performance metrics will enable resources to be more efficiently allocated.
- **Unplanned maintenance is more expensive than planned maintenance.** Large amounts of unplanned will lead to extra costs from loss production, inefficient allocation of resources, and special handling of spare parts. Carefully planning maintenance activities allows the maintenance organization to maintain a greater degree of control over costs.
- **Having a mission statement for the maintenance department and the PM program with explicit objectives and goals will help everyone work toward a common end.** Concrete metrics, that coincide with stated objectives, need to be developed so that the effectiveness of the PM program can be easily measured and tracked. Developing meaningful and relevant goals and metrics is an essential element for getting and keeping everyone involved.
- **PM activities can often be excessive (conservative).** Moving toward condition-based monitoring and predictive maintenance is necessary when resources (time, manpower, spare parts, etc.) are limited. As cost information and equipment

performance metrics are understood, PM activities can be streamlined and relegated to the most critical equipment.

### **5.3 NS Preventive Maintenance Program**

The maintenance strategy that is pursued in a body shop can have a tremendous impact on the performance of the body assembly equipment. While many types of maintenance activities can be combined to create a broad overall maintenance strategy, the maintenance activities that are planned for the NS body shops, fall primarily into the category of preventive maintenance. Although PM should merely be one component of the total maintenance program, it will comprise a relatively large portion of the NS maintenance activities. Therefore, an assessment of the planned PM program is warranted, to provide a better understanding of how the program might impact equipment performance.

A preventive maintenance program can be evaluated based on a variety of characteristics. Some of the key factors of concern when developing a program are labor costs, spare parts inventory, and scheduling requirements. The next section will examine the labor costs associated with the PM program developed for the St. Louis NS underbody systems by analyzing the time requirements for the PM tasks recommended by the equipment manufacturer.

#### **5.3.1 Methodology for Estimating Labor Requirements**

To estimate the labor requirements, the amount of time required to perform the PM tasks associated with the underbody systems has to first be determined. In order to determine the time requirements, the following information is essential: frequency of task, time to complete task, scheduling constraints, and job assignment for task. This information was collected from raw data listed in preventive maintenance worksheets, provided by DCT. The following information was available for each component in the underbody systems that requires PM.

- component name
- number of components
- type of PM activity to be performed
- skilled trade classification assigned to perform PM task
- time required to complete PM activity
- recommended frequency to perform PM activity
- when the PM activity can be performed

The data provided in the preventive maintenance worksheets are used to estimate the time requirements for each skilled trades job classification in the maintenance organization.

The skilled trade classifications for the St. Louis Assembly Plant are electrician, millwright, pipefitter, toolmaker, and welder repair. Each trade classification adheres to strict work rules which limit the type of activities that can be done by a particular trade group. For example, electricians are responsible for all electrical components and pipefitters are responsible for plumbing and hydraulics. Even if a task is simple enough to be performed by anyone with a basic understanding of the equipment, it has to be done by a skilled trades person who is responsible for that particular type of job because the lines of demarcation make work rules very explicit.

The recommended frequencies to perform PM activities are based on the assumption that the equipment is operating 5 days per week, 2 shifts per day, 8 hours per shift.

Frequencies are reported as daily, weekly, monthly, semi-annual, or annual. The PM activities can be scheduled at various times during the day. Activities which can be completed during a normal production day can be scheduled during break or lunch, depending on the amount of time required to perform the activity. All activities which cannot occur during a regular production day are scheduled for the weekend. Those activities requiring 15 minutes or less were classified as tasks which can be done during break, activities needing between 15 and 30 minutes were classified as lunch tasks, and activities that required more than 30 minutes to complete were scheduled as weekend tasks. Although some visual inspections and other PM activities may be able to take

place during production (while equipment is operating), these activities are not identified as such in the PM worksheets.

#### ***5.3.1.1 Sorting the Tasks***

The PM tasks were separated into several different categories by sorting the data initially into groups according to the trade assignment. Next the tasks within each trade group were further categorized by sorting them according to the frequency of the tasks. The tasks in each resulting group were then separated according to when the tasks could be scheduled.

Once the PM activities were completely sorted, the time,  $t$ , requirements were calculated for each trade classification using the matrix in Table 1, where  $t_{11}$  represents the total time for all daily tasks which can be performed during breaks,  $t_{12}$  represents the total time for all daily tasks which can be performed during lunch, etc. The row total represents the amount of time required to perform PM tasks for the corresponding frequency category. To determine the total time requirement for each trade classification, the time required to perform the tasks for each frequency category has to be converted to like units. For example, to add the times for daily and weekly tasks, the time spent on weekly tasks has to be converted to units of “daily time,” or vice versa.

For each trade classification, the total time requirements are calculated initially in units of annual time, i.e. the average amount of time spent annually performing PM tasks. To calculate the annual time requirements, the time requirement for each task is multiplied by a numerical factor related to the task frequency. For example, the daily tasks are multiplied by 300 (assuming 6 production days per week and 50 production weeks per year, gives 300 days that PM tasks have to be done). Table 2 has a complete list of the frequencies, their corresponding multipliers, and a few key assumptions. To calculate the daily time requirements, the annual time requirement for each task is divided by 365 (assuming maintenance tasks can be done seven days a week, 52 weeks a year).



<b>Scheduling Opportunities</b>	<b>Break</b>	<b>Lunch</b>	<b>Weekend</b>	<b>Totals</b>
<b>Task Frequency</b>				
<b>Daily</b>	$t_{11}$	$t_{12}$	$t_{13}$	$\sum_{j=1}^3 t_{1j}$
<b>Weekly</b>	$t_{21}$	$t_{22}$	$t_{23}$	$\sum_{j=1}^3 t_{2j}$
<b>Monthly</b>	$t_{31}$	$t_{32}$	$t_{33}$	$\sum_{j=1}^3 t_{3j}$
<b>Semi-Annually</b>	$t_{41}$	$t_{42}$	$t_{43}$	$\sum_{j=1}^3 t_{4j}$
<b>Annually</b>	$t_{51}$	$t_{52}$	$t_{53}$	$\sum_{j=1}^3 t_{5j}$

**Table 1: Calculating Time Requirements for Each Trade Classification**

<b>Task Frequency</b>	<b>Multiplier</b>	<b>Assumptions</b>
Daily	300	6 production days per week
Weekly	50	2 weeks for annual shut down
Monthly	12	
Semi-Annually	2	
Annually	1	

**Table 2: Annual Time Requirement Multipliers**

The total annual time,  $t_a$ , requirement for each trade classification is calculated using the matrix shown in Table 3, where  $t_{a11}$  is the total time per year spent for all daily tasks that can be performed during breaks,  $t_{a12}$  is the total time per year spent for all daily tasks that can be performed during lunch, etc. The row total represents the amount of time per year required to perform PM tasks for the corresponding frequency category and the column

total represents the amount of time per year required to perform PM tasks for the corresponding scheduling opportunity. The grand total is the total time required, per year, to perform all recommended PM tasks for each trade classification.

Scheduling Opportunities \ Task Frequency	Break	Lunch	Weekend	Totals
Daily	$t_{a11}$	$t_{a12}$	$t_{a13}$	$\sum_{j=1}^3 t_{a1j}$
Weekly	$t_{a21}$	$t_{a22}$	$t_{a23}$	$\sum_{j=1}^3 t_{a2j}$
Monthly	$t_{a31}$	$t_{a32}$	$t_{a33}$	$\sum_{j=1}^3 t_{a3j}$
Semi-Annually	$t_{a41}$	$t_{a42}$	$t_{a43}$	$\sum_{j=1}^3 t_{a4j}$
Annually	$t_{a51}$	$t_{a52}$	$t_{a53}$	$\sum_{j=1}^3 t_{a5j}$
Totals	$\sum_{i=1}^5 t_{ai1}$	$\sum_{i=1}^5 t_{ai2}$	$\sum_{i=1}^5 t_{ai3}$	$\sum_{i=1}^5 \sum_{j=1}^3 t_{aij}$

**Table 3: Calculating Annual PM Time Requirements for Each Trade Classification**

The total daily time requirement for each trade classification is calculated using the matrix presented in Table 4, where  $t_{d11}$  is the total time per day spent for all daily tasks that can be performed during breaks,  $t_{d12}$  is the total time per day spent for all daily tasks that can be performed during lunch, etc. The row total represents the amount of time per day, on average, required to perform PM tasks for the corresponding frequency category and the column total represents the amount of time per day, on average, required to perform PM tasks for the corresponding scheduling opportunity. The grand total is the total time required, per day, to perform all recommended PM tasks for each trade classification.

<b>Scheduling Opportunities</b> <b>Task Frequency</b>	<b>Break</b>	<b>Lunch</b>	<b>Weekend</b>	<b>Totals</b>
<b>Daily</b>	$t_{d11}$	$t_{d12}$	$t_{d13}$	$\sum_{j=1}^3 t_{d1j}$
<b>Weekly</b>	$t_{d21}$	$t_{d22}$	$t_{d23}$	$\sum_{j=1}^3 t_{d2j}$
<b>Monthly</b>	$t_{d31}$	$t_{d32}$	$t_{d33}$	$\sum_{j=1}^3 t_{d3j}$
<b>Semi-Annually</b>	$t_{d41}$	$t_{d42}$	$t_{d43}$	$\sum_{j=1}^3 t_{d4j}$
<b>Annually</b>	$t_{d51}$	$t_{d52}$	$t_{d53}$	$\sum_{j=1}^3 t_{d5j}$
<b>Totals</b>	$\sum_{i=1}^5 t_{di1}$	$\sum_{i=1}^5 t_{di2}$	$\sum_{i=1}^5 t_{di3}$	$\sum_{i=1}^5 \sum_{j=1}^3 t_{dij}$

**Table 4: Calculating Daily PM Time Requirements for Each Trade Classification**

### 5.3.2 Preventive Maintenance Requirements for NS Underbody Systems

#### 5.3.2.1 Time Requirements per Trade Classification

Table 5 shows a summary of the estimates of PM time requirements for the St. Louis NS underbody systems. A complete presentation of PM time requirements, separated by task frequency and scheduling opportunities for each trade classification, can be found in Appendix A. Estimates for the labor requirements for each trade assignment are made ignoring scheduling constraints and assuming that for every 40 hours of PM required during one week, 1 person is need. Determining the exact labor requirements considering all scheduling constraints is a much more detailed process than the one presented here.

The exact windows of opportunity available to perform PM activities has to be known. Also, the maximum amount of hours one worker can be scheduled per day and per week must be known.

On average, the time requirements for preventive maintenance for the underbody system is approximately 83 hours per day. 85% of that time is devoted to welder repair tasks, 11% to toolmaker tasks, 2% to electrician tasks, and 1% to both millwright and pipefitter tasks.

Skilled Trade Assignment	Time Required to Complete PM Tasks			Percentage of Total	Labor Requirements
	Per Day [hours]	Per Week [hours]	Per Year [hours]		
Electrician	1.6	11.4	595	2%	1 person
Millwright	1.0	6.9	357	1%	1 person
Pipefitter	0.6	4.4	231	1%	1 person
Toolmaker	9.5	66.4	3452	11%	2 people
Welder Repair	70.3	493.2	25,648	85%	12 people
<b>Total</b>	<b>83.0</b>	<b>582.3</b>	<b>30,283</b>	<b>100%</b>	<b>17 people</b>

**Table 5: Summary of NS PM Time and Labor Requirements by Trade Assignment**

**Welder Repair**

Approximately 12 people will be required to perform the welder repair tasks. On average, 70 hours of PM is required daily, which is about 490 hours per week.

**Toolmaker**

Approximately 2 people will be required to perform the toolmaker tasks. On average, 9.5 hours of PM is required daily, which is about 66 hours per week.

**Electrician**

One person will be required to perform the electrician tasks. On average, 1.6 hours of PM is required daily, which is about 11 hours per week.

### **Millwright**

One person will be required to perform the millwright tasks. On average, 1 hour of PM is required daily, which is about 7 hours per week.

### **Pipefitter**

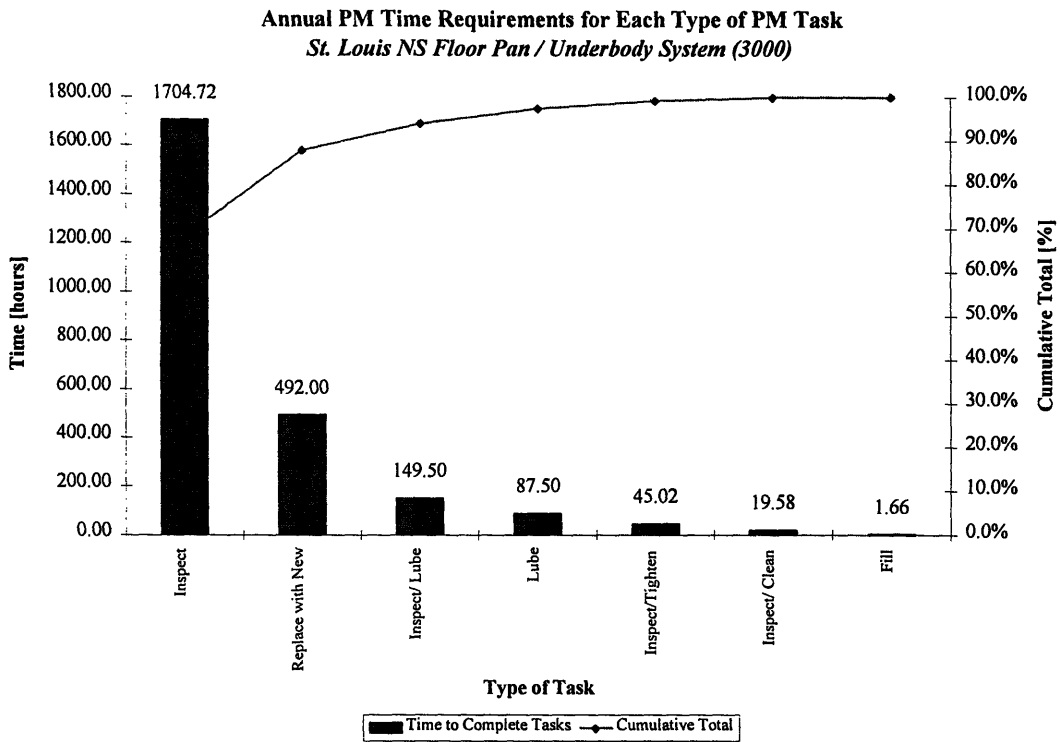
One person will be required to perform the pipefitter tasks. On average, 0.6 hours of PM is required daily, which is about 4 hours per week.

#### ***5.3.2.2 PM Task Composition for the NS Floor Pan / Underbody Subsystem***

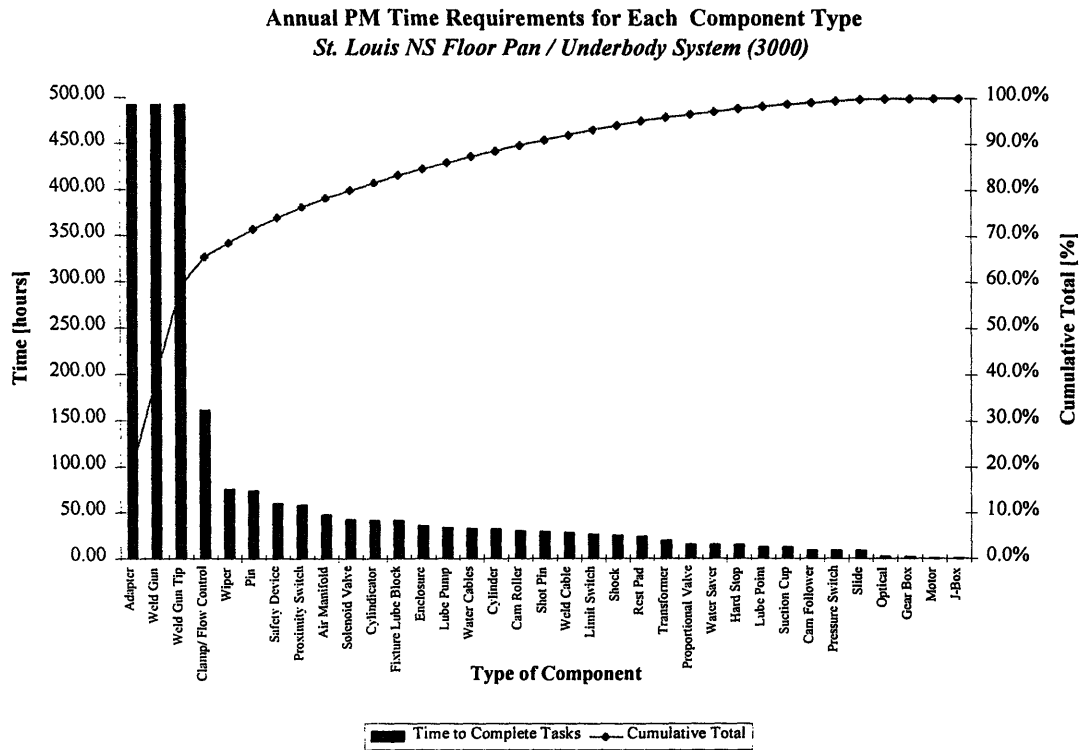
Another method of evaluating a PM program involves an analysis of how time is spent performing various tasks. The PM activities recommended for the floor pan / underbody subsystem are studied to determine the composition of the activities, and to learn which activities are the most time consuming. The tasks were found to fall into several main groups: fill, inspect, inspect & clean, inspect & lube, inspect & tighten, lube, and replace with new. The total time required to perform the recommended PM tasks for this subsystem is approximately 2500 hours per year. Figure 6 shows the distribution of PM time requirements for each task. For the St. Louis NS floor pan / underbody subsystem, over 80% of the preventive maintenance activities fall into two major categories:

- 1) inspecting equipment for malfunctioning parts or wear, and
- 2) replacing old components with new.

In the floor pan / underbody system, there are thirty-five components requiring PM with 29% (10 out of 35) of the components accounting for 80% of the time required for preventive maintenance on the floor pan and underbody system (See Figure 7). The three largest time requirements come from preventive maintenance tasks related to the weld guns (adapters, guns, and tips) which require daily maintenance.

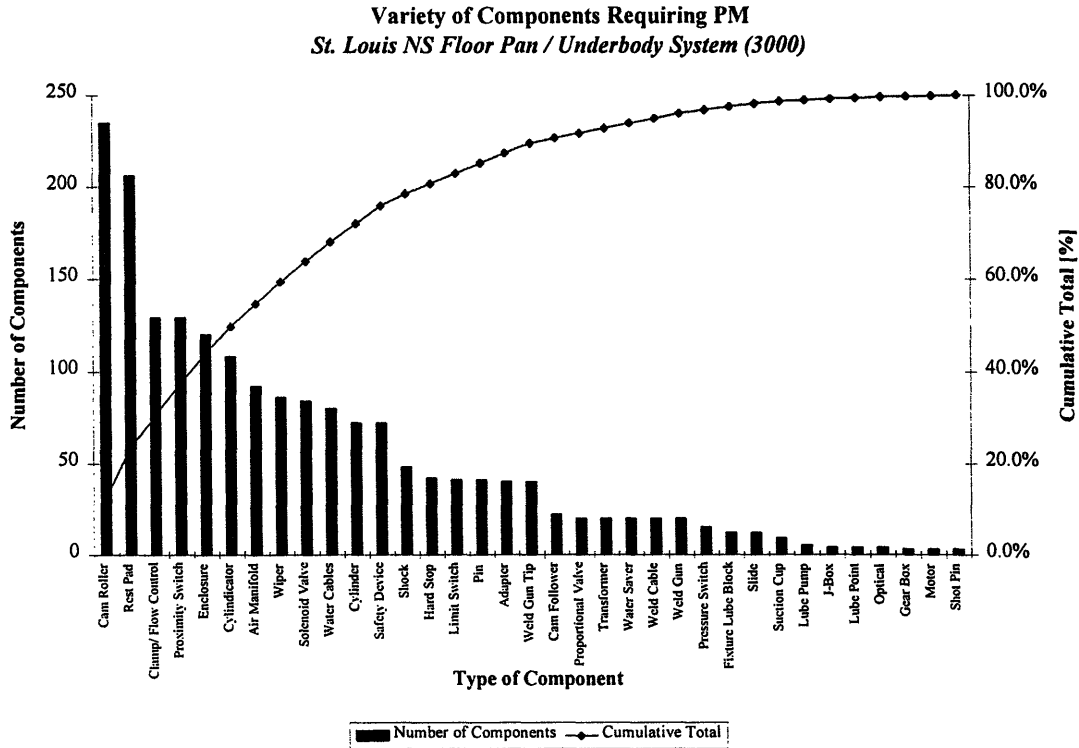


**Figure 6: Annual Time Requirements for PM Task Type**



**Figure 7: Annual PM Time Requirements for Component Type**

More than 1800 individual components require preventive maintenance with approximately 350 distinct PM tasks. Figure 8 shows the distribution and variety of components that require PM for the floor pan / underbody subsystem.



**Figure 8: NS Floor Pan / Underbody Component Variety**

### 5.3.3 Remarks about the NS PM Program

The recommended PM tasks seem somewhat conservative. Since the majority of the tasks consist of inspection activities, actual repair time if something has failed or deteriorated is not accounted for, therefore even more time could be required when repair is necessary. Additionally, because inspections can be subjective, it may be very difficult to achieve consistency throughout the maintenance organization with regards to completing the PM activities. Some workers will be too cautious and conservative, while others may let equipment deteriorate too long before action is taken.

The estimates made in this section only represent a fraction of the total body shop systems. A similar type analysis could be done for the remaining body shop systems (aperture, framing, etc.), but the analysis presented here can serve as a good guideline and indicator of what type of labor requirements are necessary to complete the proposed PM tasks for the NS body shops. Having 17 people strictly assigned to perform PM tasks on the underbody systems would roughly double the maintenance personnel assigned to that equipment. This may appear unreasonable given the current structure of the maintenance organization and the manner in which work is organized. Nevertheless, there are alternatives to accomplishing the necessary planned maintenance requirements. The recommended PM procedures require a significant amount of inspection, which could potentially become a shared responsibility of the production operators. Although there could be conflicts with work rules and union contracts, this option needs to be considered as a viable alternative for the future. Also, there are many opportunities to reduce labor requirements for performing PM by automating some of the activities or implementing PdM techniques. For example, instead of having someone manually inspect conveyors, an automated chain monitor system could be implemented which could electronically signal when the conveyor has stretched beyond some acceptable limit.



## **6. Equipment Reliability Assessment**

Equipment reliability is such an important issue for several reasons. With the marketplace growing more intensely competitive, it is becoming increasingly critical that companies be able to have firm control over their products and processes. Gradual deterioration, as well as sudden breakdown, of manufacturing process equipment can have a major negative impact on product quality and availability. Therefore it is of utmost important to minimize the negative effects of unexpected equipment failures. To address this issue, many reliability analysis techniques can be employed to evaluate equipment performance and to determine how to optimize process assembly systems. This section will examine some of the options available for assessing equipment performance. Particular attention will be paid to those techniques and methodologies used during NS process development activities. Since equipment reliability and availability are of considerable importance, a more detailed analysis of various methods for determining reliability and availability will be presented.

### **6.1 General Availability and Reliability Analysis**

Many mistakenly use the terms reliability and availability interchangeably. The major difference between the two is that reliability measures do not include maintenance issues, while availability measures incorporate both reliability and maintainability. Reliability is a measure of the time that a system will work without repair or failure. Availability, on the other hand, is a measure of the percentage of time that a system is working over a long period of time, during which it can fail, and be repaired often.

Conducting a highly accurate reliability analysis of complicated electro-mechanical systems is quite a challenge that is exacerbated by the lack of dependable sources of failure data for mechanical components. “ If reliability data for the sub-sections, whether derived from operating experience with the same or similar plant, or from published data sources, is not available, analysis of system reliability becomes difficult to quantify.” (Davidson, 1988) To conduct reliability analysis, it is essential to have a good

understanding of the failure distribution associated with the equipment being analyzed. However, obtaining the data to estimate failure distributions is not a trivial task. Since body process equipment is so unique and operates in a wide range of environments, the relevant failure data for any one type of equipment may be very limited.

To approximate failure distributions, several families of statistical distribution curves are commonly used. For basic reliability analysis, using an exponential failure distribution is a reasonable assumption. If adequate data is available, Weibull analysis can be more accurate because it has varying shape parameters which creates a great deal of flexibility and typically fits most lifetime data better than some other distributions. Because of the lack of available data, the following analysis will assume that the failure distribution is exponential, thus the failure rate can be determined from the mean time before failure data. Equipment reliability with an exponential failure distribution can be calculated using the following equation, where  $R$  is reliability,  $\lambda$  is the failure rate, and  $t$  is time. (Carter, 1986)

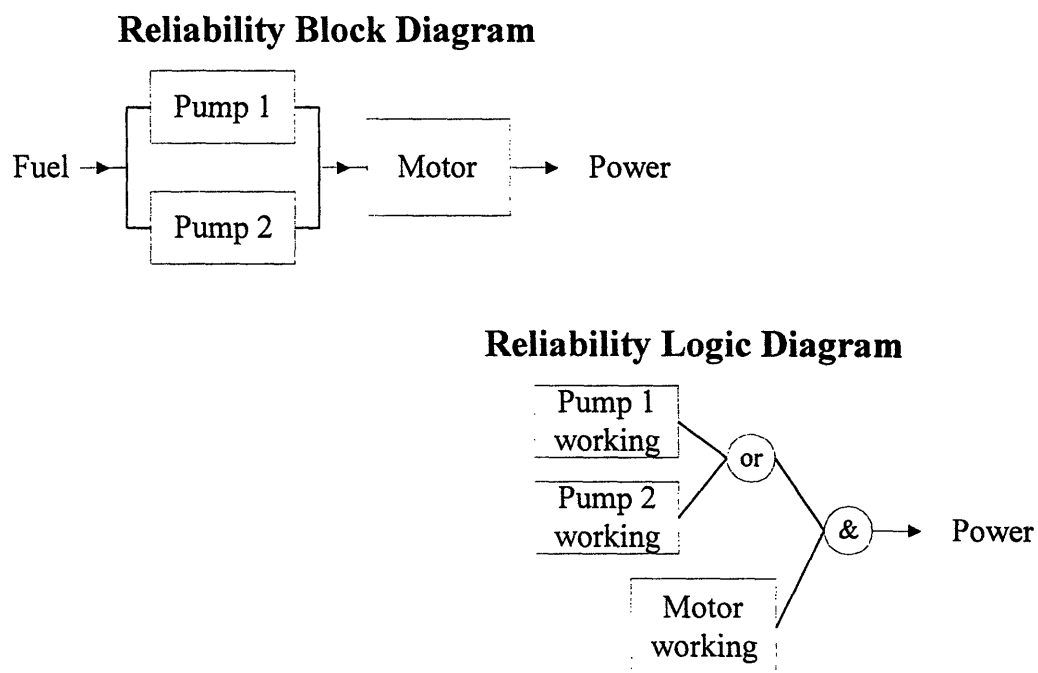
$$R = e^{-\lambda t} \quad (1)$$

## **6.1.1 Reliability Analysis Tools**

### ***6.1.1.1 Reliability Diagrams***

Two types of block diagrams are useful for representing and modeling systems for reliability analysis: reliability block diagrams and reliability logic diagrams. A reliability block diagram schematically illustrates all components of the system that is being analyzed with the connections between the components representing functional, rather than physical, connections. Reliability logic diagrams are also schematic representations of systems which use logic gates, instead of symbolic flow lines, to represent the interaction of components within the system. A comparison of the RBD and RLD for a simple pump-motor system is shown in Figure 9. When trying to analyze systems on a detailed component level, reliability block diagrams are more useful for electrical systems

than mechanical systems. Since mechanical systems tend to be a serial connection of components, this analysis often doesn't add much value. Therefore, when modeling mechanical systems, some reliability engineers "bulk components into fairly substantial subsystems," (Carter, 1988) in order to better utilize the electrical systems approach. "It is contended that the multi-component sub-systems exhibit the constant failure rate of the pseudo-random condition and can then be treated in the same manner as electronic components." (ibid.)



**Figure 9: Comparison of a Reliability Block Diagram and Reliability Logic Diagram for a Simple Pump-Motor System**

### 6.1.2 Equipment Assessment Definitions

Kapur and Lamberson (1977) define the following terms which are useful for evaluating equipment performance.

**OR = operational readiness:** probability that either a system is operating or can operate satisfactorily when the system is used under stated conditions. Operational readiness can be expressed in the following terms.

$$OR = \frac{\text{operating time} + \text{idle time}}{\text{operating time} + \text{idle time} + \text{downtime}} \quad (2)$$

**A = steady state availability:** probability that a system is operating satisfactorily at any point in time and considers only operating time and downtime, thus excluding idle time. The following equation is a mathematical representation of steady state availability, where MTBF is defined as the mean time before failure and MTTR is defined as the mean time to repair.

$$A = \frac{\text{operating time}}{\text{operating time} + \text{downtime}} = \frac{MTBF}{MTBF + MTTR} \quad (3)$$

**A<sub>i</sub> = intrinsic availability:** probability that a system is operating in a satisfactory manner at any point in time when used under stated conditions; time is limited to operating and active repair time. The following equation is a mathematical representation of intrinsic availability, where MART is defined as mean active repair time.

$$A_i = \frac{\text{operating time}}{\text{operating time} + \text{active repair time}} = \frac{MTBF}{MTBF + MART} \quad (4)$$

The main difference between steady state and intrinsic availability, is the mean repair term. MTTR (mean time to repair) includes all downtime associated with an equipment failure while MART (mean active repair time) includes only actual time spent repairing a failure, excluding time spent waiting for parts or waiting for maintenance personnel. While operational readiness seems to be a useful internal metric for evaluating equipment performance, availability may be a more suitable metric for assessing the equipment manufacturers' progress toward specific equipment performance objectives since the

availability terms exclude idle time for which the equipment manufacturers are not accountable.

## **6.2 Methods for Evaluating NS Equipment Performance**

Each of the two primary suppliers for the NS body assembly systems are required to assess the equipment performance of their respective systems during the design and production stages. One of the primary performance objectives for the NS body assembly systems is to achieve 95% uptime. Although there are some differing opinions about the exact procedure for determining and measuring this objective, minimizing loss production time because of equipment failures seems to be the common theme that surfaces when this assessment issue is debated. Reliability and availability are two measures that can provide useful information about equipment performance. A major portion of the assessment consists of computer simulation studies, availability analysis, and failure analysis in addition to other validation techniques. Each supplier has a different approach to evaluating equipment, partially due to a lack of standard definitions and procedures among Chrysler and its suppliers for measuring equipment performance. The following sections will examine and evaluate the different approaches pursued by the equipment suppliers and propose a third method for evaluating equipment system performance.

### **6.2.1 Method 1**

Chrysler requires its major body assembly system suppliers to conduct a simulation study during the process development process. The stated purpose of the simulation study done by one supplier (DCT) is to build “a computer simulation model of the proposed design of the 1996 Chrysler NS Underbody Assembly Line to assist in the systems evaluation and validation process. The simulation will be employed to assess system performance under a variety of operational conditions.” This tool is used in an attempt to understand system performance parameters before the systems are built. The effectiveness and validity of this tool is largely dependent upon the data and assumptions that are used as input for the simulation models. The downtime data used in this procedure is provided

by a Chrysler plant and is used to determine the repair distribution. It is unclear if the repair times presented include waiting time, for maintenance personnel or replacement parts (MART vs. MTTR). The failure distribution is modeled as exponential, however there is no specific reference to the data source. With values for MTTR and MTBF, availability can be calculated using Equation 3. However, in the study done as a part of this procedure, this measure is incorrectly referred to as reliability instead of availability. Some of the key assumptions used in this analysis are listed below.

- there is no variation in the process cycle times for different product types (i.e. LWB, SWB, AWD)
- mean time to repair is 2.5 minutes
- mean time before failure is 497.5 minutes (or 8.3 hours)
- “reliability” was calculated using the following formula:

$$R = \frac{MTBF}{MTBF + MTTR}$$

- “reliability” for a station of 4 weld robots is 98% (99.5% for 1 robot) with MTBF = 497.5 min. and MTTR = 2.5 min.
- “reliability” for a station of 4 weld robots is 97% (99.2% for 1 robot) with MTBF = 330.8 min. and MTTR = 2.5 min.

Other assessment techniques that were done during the process development stage include a 20 hour run, where the equipment was cycled continuously without parts, detecting and correcting the problems until the system being tested could cycle for 20 hours without failures. There were some exceptions to the rule that allowed the clock to continue running when certain stoppages occurred.

### **6.2.2 Method 2**

The assessment done by another supplier (PICO) focuses on availability as one of the key indicators of system performance. A simulation study was conducted to evaluate the system performance of the NS body assembly systems built by this supplier. The stated objective of this study is to “create a model representative of the proposed Chrysler - NS

van production process in order to evaluate the system throughput capabilities and size buffers. This model is to include downtime parameters detailed in the list of assumptions.” Values for MTTR and availability are listed in the assumptions, but there is no failure data presented or referenced. MTBF can be calculated using the formula for availability Equation 3.

Some of the major assumptions for this study are listed below.

- product style differences have no impact
  - the availability of a synchronous segment equals the availability of the individual stations and the availability of the transfer mechanisms multiplies together
  - operators always work within cycle
  - For 1 robot, availability = 99.9%
  - For clamps and lifters, availability = 99.7%
  - For transfers, MTTR = 15 min. and availability = 99.9%
  - For other tooling, MTTR = 7 min.
- (other information on MTTR and availability is not explicitly stated)

Additionally, the 20 hour run was conducted in the same manner describe in Method 1. Other techniques employed by this supplier include running equipment for 15,000 dry cycles and recording failure data, and sending reliability technicians into the plants to do availability studies for equipment that is in service.

### **6.2.3 Method 3**

Since mechanical systems, unlike many electrical systems, often tend to be a serial connection of components, there is not much value added by rigorously calculating reliability at the component level. Much more useful information can be obtained by focusing on reliability and availability at the machine or station level, with some attention given to major components. For the purpose of this system analysis, the failure rates of individual components will be de-emphasized. The focus will be on the failure rate of the

mini-systems at each station, where a mini-system is defined as the set of equipment in a given assembly line station. With the absence of an adequate base of detailed failure data and the difficulty of precisely modeling all the components of a complicated system, an approach that provides a reliable way for estimating overall system performance is useful. Since there are many deficiencies associated with building complex models, it may be more beneficial to make broad assumptions based on the data that is available, and then to try to understand major interactions within the system as opposed to understanding all the interactions of components within a particular piece of equipment. The following paragraphs will discuss a proposed methodology for evaluating and understanding system interactions by developing general models to analyze system availability and reliability.

This evaluation technique begins by considering each station in an assembly system as one complete unit. Initially, the station is considered the smallest unit for this analysis. First, each station can be categorized according to the complexity of the equipment in the station to allow rough estimates for availability and reliability to be determined. Assume that stations with more complicated tooling and equipment will have higher failure rates. Each mini-system can then be categorized into one of the three following groups, ranging from the least to greatest degree of complexity:

1. simple
2. moderate
3. complex.

After determining the appropriate category for each mini-system, estimates can be made to determine a suitable value for availability. This estimate should be based on data collected in the plant in question, at other similar plants, or in the field by the equipment suppliers. Since there was a limited amount of failure data available at the time of this research, the failure and availability numbers that will be presented are rough estimates and should serve only as guidelines. Assume that the availability for the simple, moderate, and complex systems are 99.9%, 99.5%, and 99% respectively. Then to estimate the failure rate,  $\lambda$ , the mean time before failure (MTBF) has to be calculated.



MTBF can be calculated using the following equation for availability. It should be noted that if sufficient data were available, availability would be determined using MTBF and MTTR that have been calculated from repair and failure data from the field. Rearranging the terms in Equation 3 and solving for MTBF gives the following equation.

$$MTBF = \frac{A * MTTR}{1 - A} \quad (5)$$

Assuming that  $\lambda$  is constant, the failure rate can be calculated using the following equation.

$$\lambda = \frac{1}{MTBF} \quad (6)$$

Using a MTTR of 5 minutes (a number that lies between the two values used in methods 1 and 2), the following chart summarizes the estimated values for mean time before failure and failure rate.

Mini-system Type	Availability	MTBF [hours]	$\lambda$
Simple	99.9%	83.25	$1.2 \times 10^{-2}$
Moderate	99.5%	16.58	$6.0 \times 10^{-2}$
Complex	99%	8.25	$1.2 \times 10^{-1}$

**Table 6: Failure Data for Method 3 Calculations**

To determine if these estimates and assumptions are reasonable, the focus will shift momentarily to the resulting values for MTBF shown in Table 6. For a simple station, a failure occurs on average about once a week. For a moderate station, a failure occurs about once a day, and for a complex system, a failure occurs about once a shift. In general these three scenarios seem to be reasonable, although they may not be accurate for every station in the NS body assembly systems.

The benefit of this type of analysis comes from an early focus on static reliability analysis before getting heavily involved in dynamic computer simulation. This static analysis can

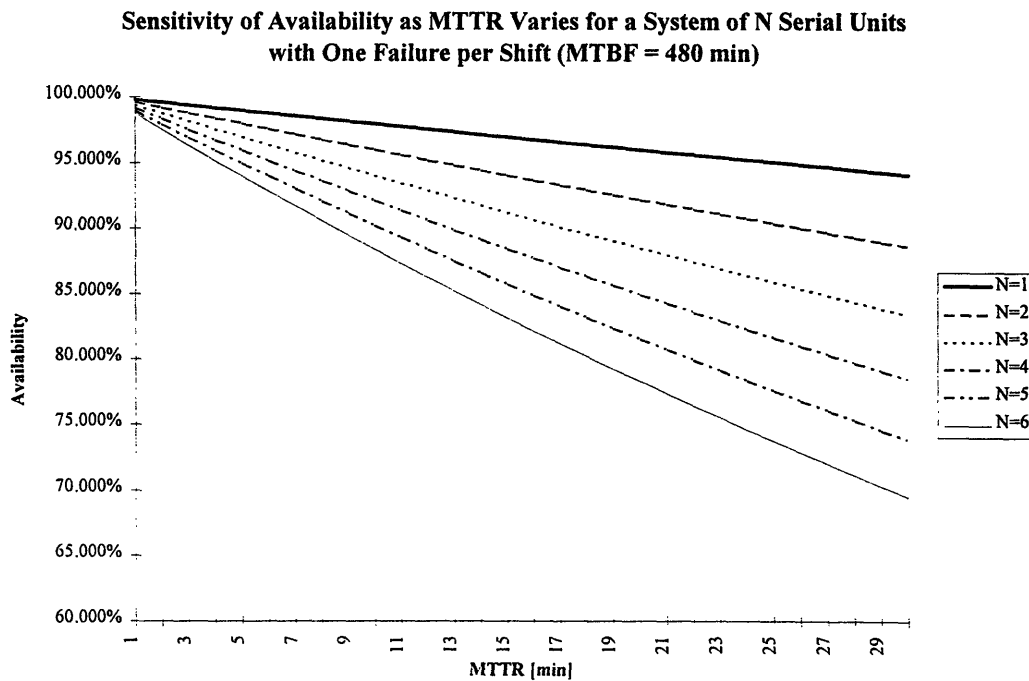
be used to emphasize the importance of carefully defining systems and understanding system interactions, which will be very useful for later dynamic simulation studies. Also, this method shifts the focus from reliability of components in isolation to reliability of “bulked components” and small subsystems.

### **6.3 Availability and Reliability Sensitivity Analysis**

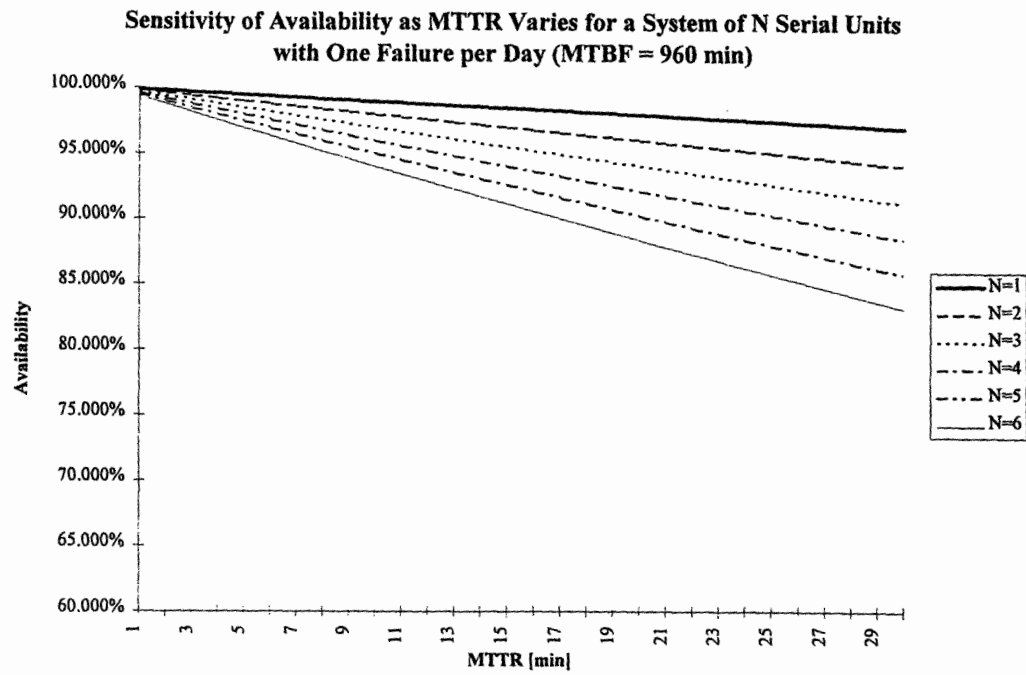
Although reliability and availability analysis can be useful, it is important to understand the limitations of the results. In order to gauge how sensitive the reliability or simulation models are to different input values, it is necessary to examine the sensitivity of these models as input values change. The following four graphs show the variation in availability as MTTR with assuming four different failure scenarios. The next four show how reliability decays over time for four different failure scenarios (using an exponential reliability function).

The availability curve in Figure 10 for  $N = 1$  unit demonstrates the effects on availability caused by using various values of MTTR. For a unit that fails on average about once per shift, the availability drops off to about 95% as MTTR reaches 30 minutes. As the number of units increases, the availability decreases at an even faster rate. For a unit that fails about once per day, the availability only drops to 97% for  $N = 1$  unit and to 83 % for  $N = 6$  units (see Figure 11). Although very few pieces of equipment are likely to average one failure per week or one failure per month, these failure rates are examined to complete the sensitivity analysis of equipment availability. In Figure 12, assuming a failure rate of once per week, the availability for 1 unit is approximately 99.5% for a MTTR of 30 minutes and 97% for 6 serial units. Once the failure rate decreases to once per month, availability is much less sensitive to changes in MTTR. As shown in Figure 13, for 1 unit, the availability only drops to 99.9% and for 6 serial units, the availability decreases to 99.3%.

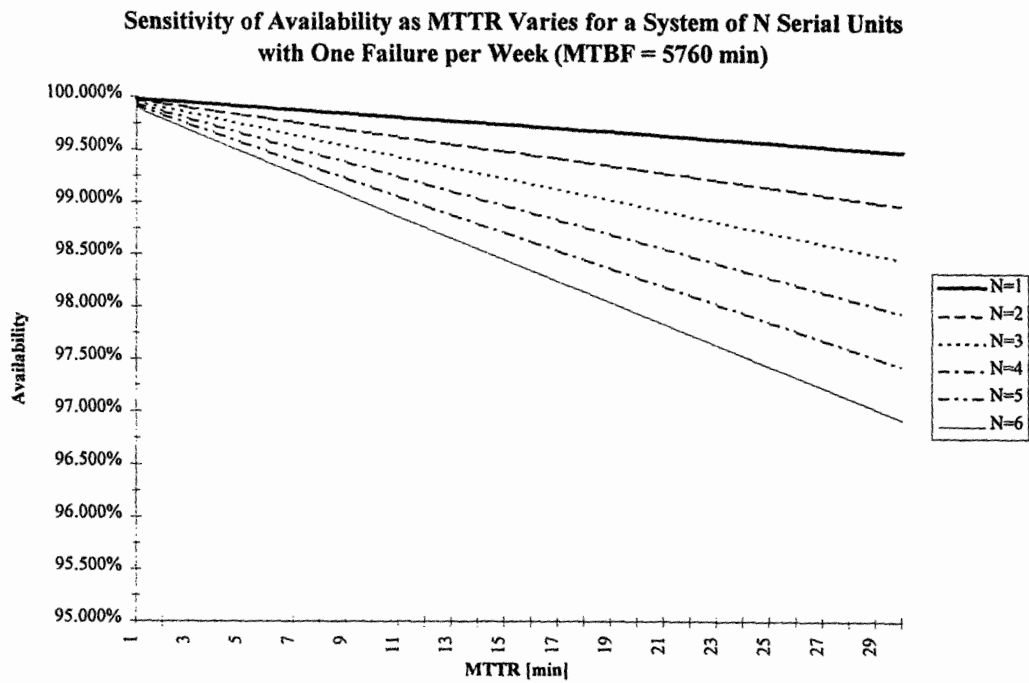
The four scenarios for availability given different failure rates and varying MTBF demonstrate that varying values for MTBF and MTTR can significantly impact the calculations for overall system availability. For variations of a few minutes in MTTR values, the resulting differences in availability can be a few percentage points for small MTTR values (<5 minutes) and even greater for larger values (>20 minutes). Availability calculations can be quite sensitive to variations in the input data, therefore it is important to vary the assumptions about MTTR or MTBF in order to determine the robustness of the estimates.



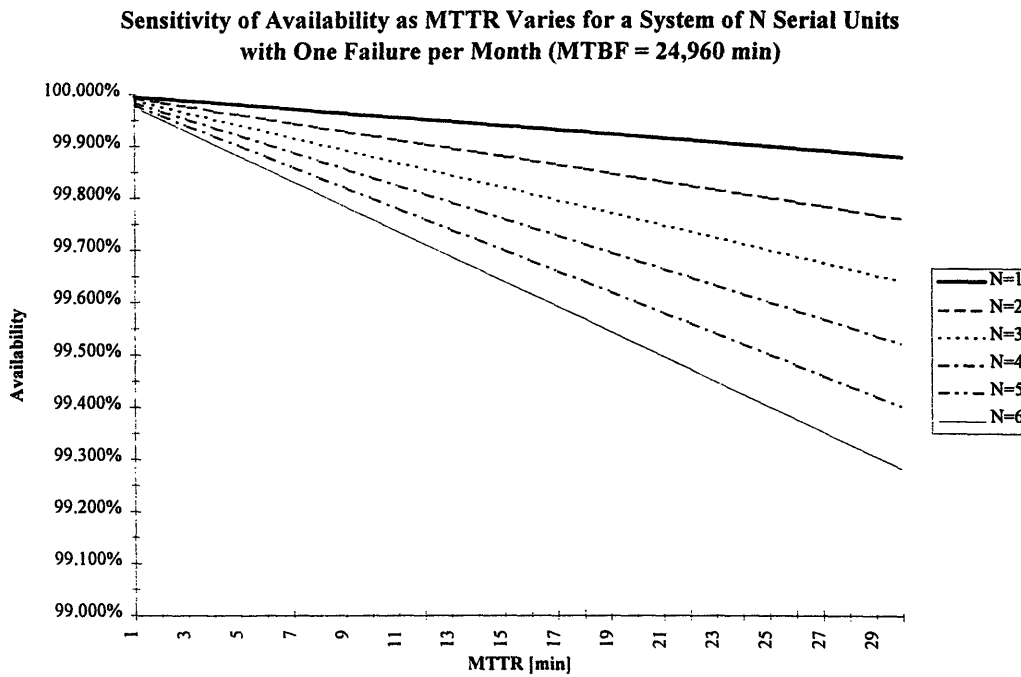
**Figure 10: Availability as a Function of MTTR for N Serial Units and One Failure per Shift**



**Figure 11: Availability as a Function of MTTR for N Serial Units and One Failure per Day**



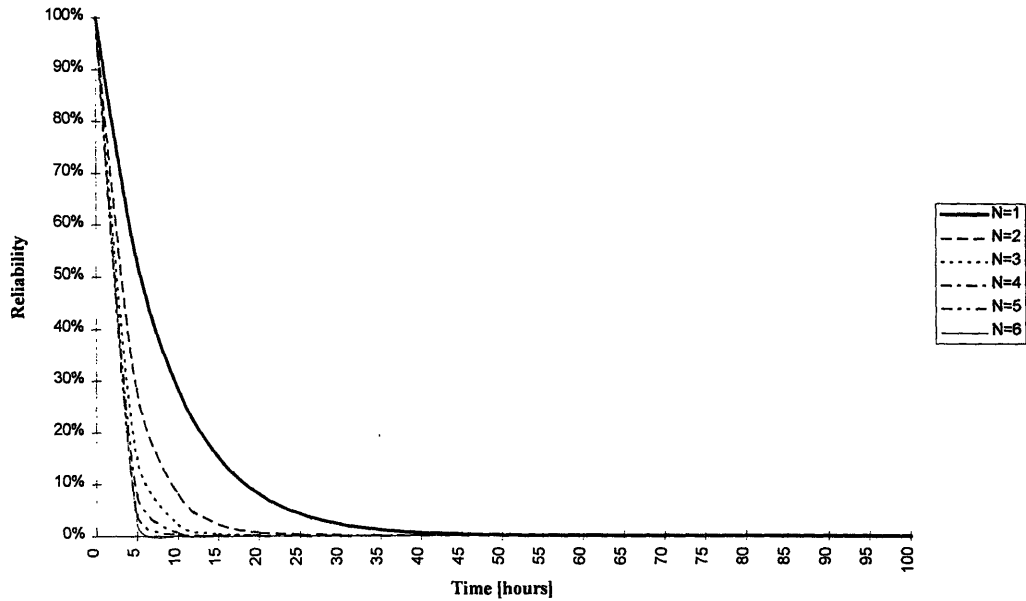
**Figure 12: Availability as a Function of MTTR for N Serial Units and One Failure per Week**



**Figure 13: Availability as a Function of MTTR for N Serial Units and One Failure per Month**

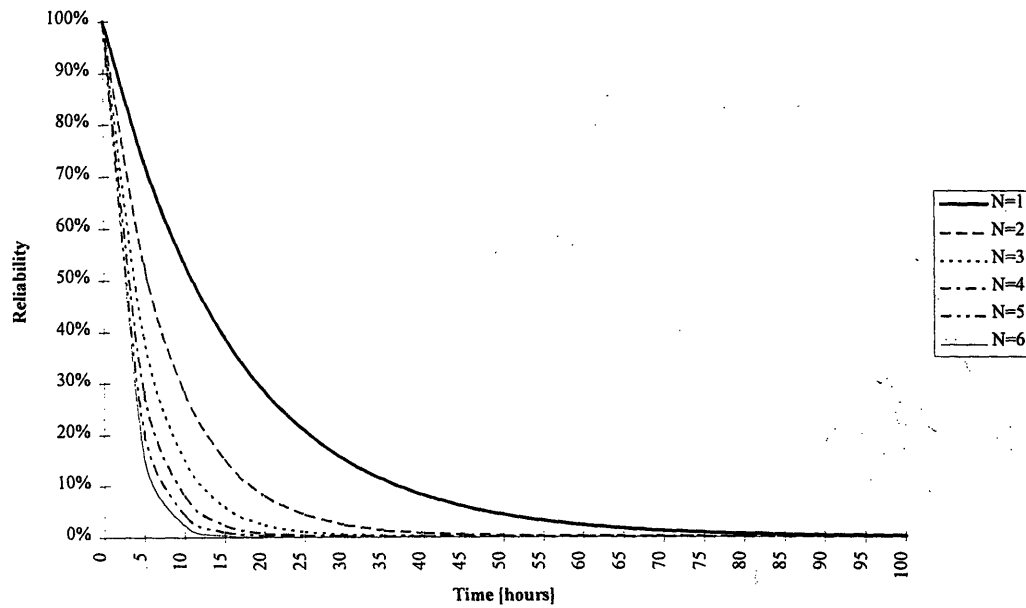
Both Figure 14 and Figure 15 show how rapidly reliability decays for serial systems with high failure rates. For a failure rate of once per shift, reliability approaches zero by the end of one shift (8 hours) for  $N > 1$ . Similarly for a failure rate of once per day, reliability approaches zero by the end of one day for  $N > 1$ . While the reliability curves in Figure 16 and Figure 17 are not as dramatic as the previous two sets, the reliability still drops below 90% very quickly. Changes in the failure rate from once per shift to once per month have a rather significant effect on the resulting reliability. As the number of units is increased, the system reliability generally decreases at a slower rate. This analysis implies that failure rate has to be considered very carefully before using it to conduct reliability calculations. Also, this sensitivity analysis implies that reliability decreases so fast for high failure rates that strict reliability analysis may have limited applications, since the reliability values approach zero so quickly.

**Reliability Over Time for a System of N Serial Units with One Failure per Shift (MTBF = 8 hours)**

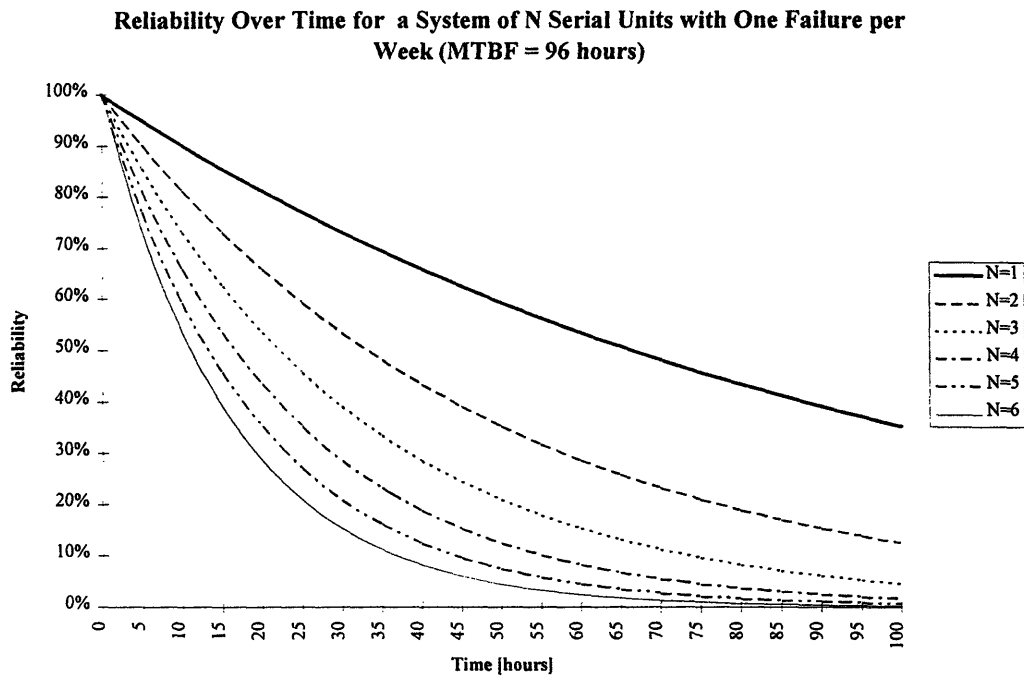


**Figure 14: Reliability as a Function of Time for N Serial Units and One Failure per Shift**

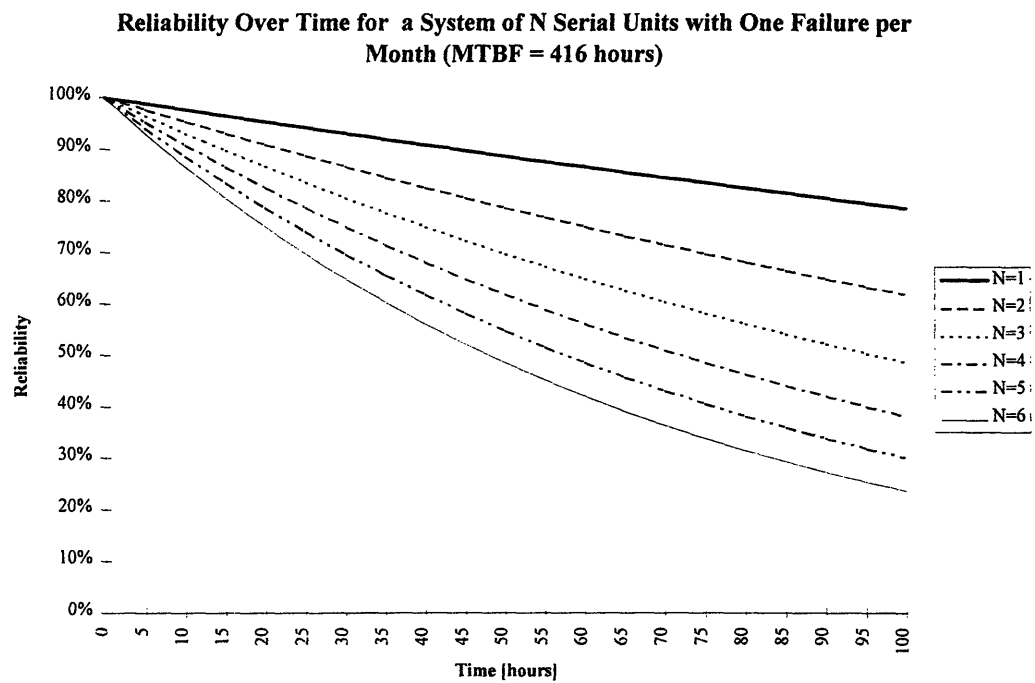
**Reliability Over Time for a System of N Serial Units with One Failure per Day (MTBF = 16 hours)**



**Figure 15: Reliability as a Function of Time for N Serial Units and One Failure per Day**



**Figure 16: Reliability as a Function of Time for N Serial Units and One Failure per Week**



**Figure 17: Reliability as a Function of Time for N Serial Units and One Failure per Month**

## 7. Case Study

### 7.1 Background

The NS floor pan and underbody subsystem (3000), one of the major assembly subsystems for the NS body shop, will be used in this analysis. The diagram in Figure 18 illustrates the physical process flow of the floor pan / underbody assembly subsystem. A more detailed system description is located in Appendix B. In this case study, the work week consists of 2 shifts each lasting 40 hours per week.

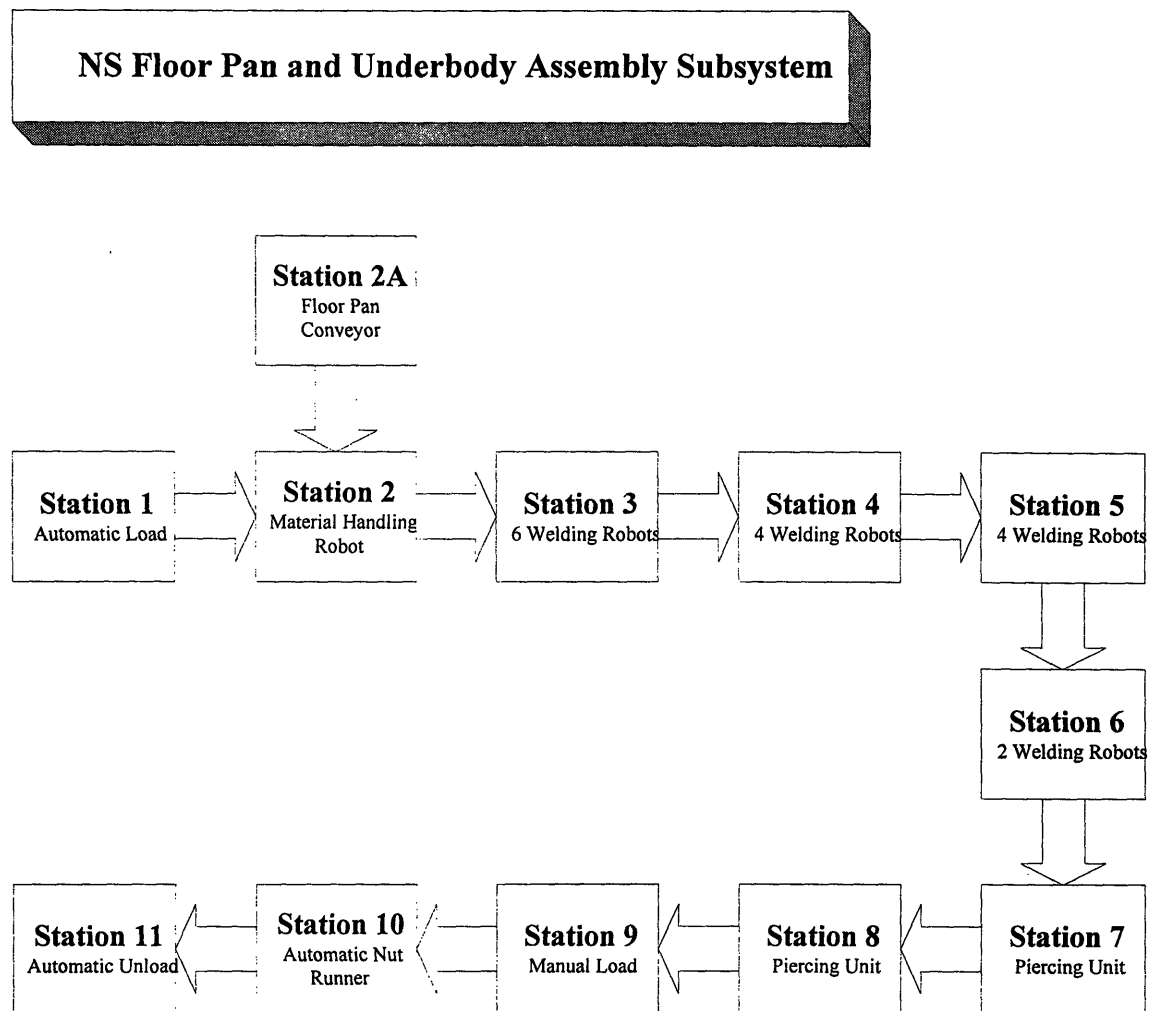


Figure 18: Floor Pan / Underbody System Process Flow



## Reliability and Availability Analysis

The reliability logic diagram in Figure 19 represents the logical flow of operations for system 3000 where,

P1 represents processes occurring at Station 1,

P2 represents processes occurring at Station 2,

↓

↓

PN represents processes occurring at Station N,

L&C1 represents the first phase of the lift and carry transfer process,

L&C2 represents the second phase of the lift and carry transfer process,

OHT1 represents the first phase of the overhead transfer process, and

OHT2 represents the second phase of the overhead transfer process.

The “and” function, in the reliability logic diagram represents a juncture at which those activities flowing into the node have to function successfully before the activity flowing out of the node can begin. For example before the first phase of the lift and carry operation (L&C1) can begin, processes 1-5 have to finish operating successfully.

Similarly, after L&C1 has successfully finished and when Station 6 is clear (after the first stage of the overhead transfer is completed), the second phase of the lift and carry operation begins. The overhead transfer mechanism engages (OHT1) when processes 6-10 have completed successfully. The second phase of the overhead transfer (OHT2) begins after OHT1 is successfully finished and when Station 11 is clear. The cycle begins again once L&C2 and OHT2 successfully finish.

The following system analysis does not encompass a detailed component level analysis of reliability and availability, but rather focuses on performance at the equipment and “mini-system” level. To facilitate the analysis of the floor pan and underbody system, reliability block diagrams are used so that processes 1-5 and 6-10 can be examined separately and then each simplified into an equivalent system. The reliability block diagram in Figure 20 represents the first five processes, Section A, which occur at Stations 1-5. The processes can be represented as a simple series system in which all individual units of the system must function successfully in order for the whole system to

function successfully. The reliability block diagram in Figure 21 represents processes 6-10, Section B, which occur at Stations 6-10 respectively. These processes can also be modeled as a simple series system.

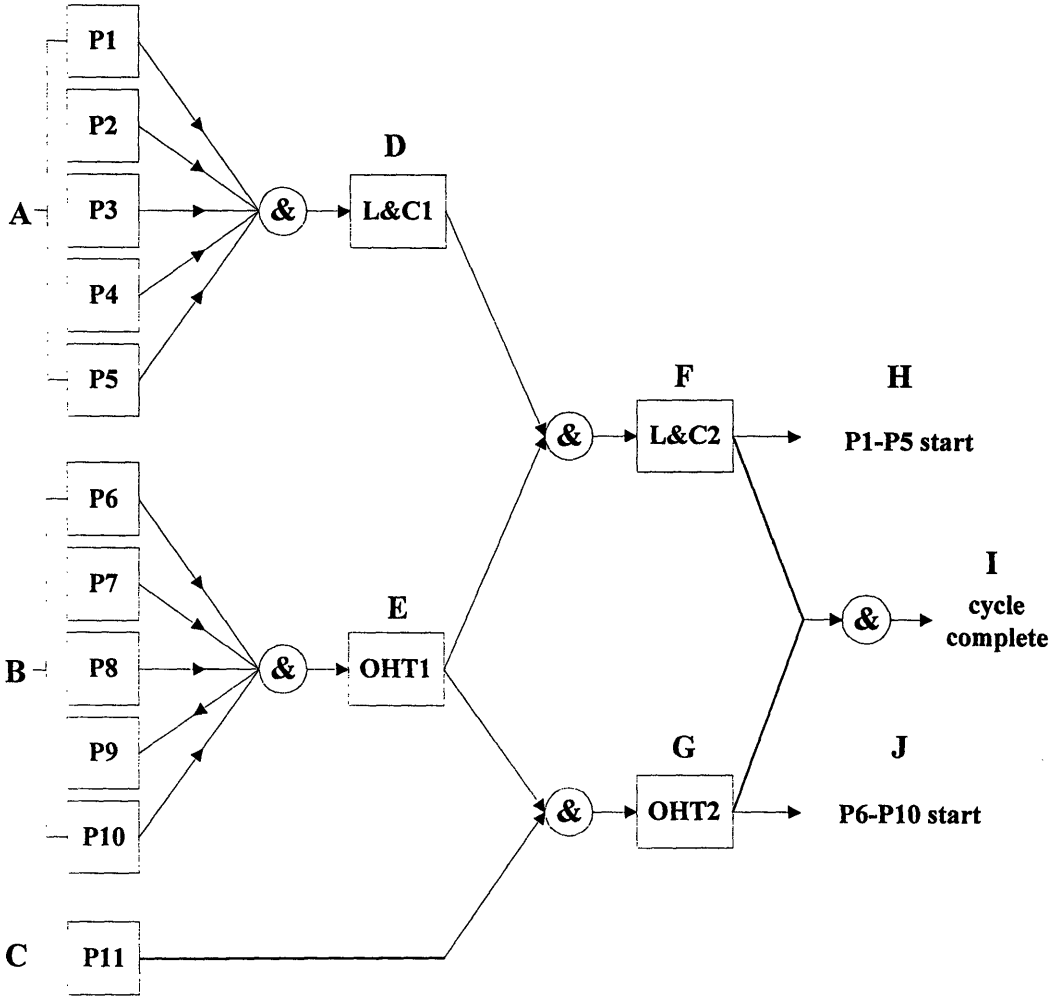


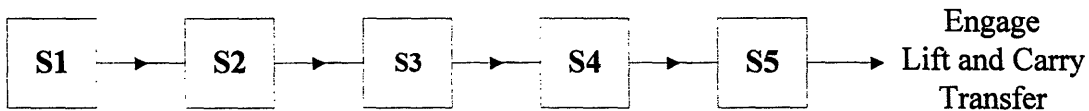
Figure 19: System 3000 Reliability Logic Diagram

In order to calculate both reliability and availability, data for failure rate / mean time before failure must be known. Approximating this information can greatly skew the

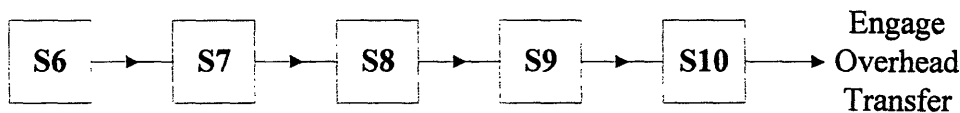
calculations if the approximations are not accurate. For a serial system, reliability and availability are calculated using the following equations:

$$R_S = R_1 \times R_2 \times R_3 \times \dots \times R_n \quad (7)$$

$$A_S = A_1 \times A_2 \times A_3 \times \dots \times A_n \quad (8)$$



**Figure 20: System 3000 Reliability Block Diagram for Section A**



**Figure 21: System 3000 Reliability Block Diagram For Section B**

After obtaining estimates for availability and failure data for each type of mini-system (see previous chapter), the reliability and availability calculations can be made for the floor pan and underbody system using Equations 7 and 8 along with the assumptions of the three methods presented in the previous chapter. The results, using all three methods, are presented in Table 7 for Section A shown in Figure 20, and the results for Section B, shown in Figure 21, are presented in Table 8.

For these calculations, the robots and the transfer mechanisms are considered as separate entities. Therefore, the values for reliability and availability at each station do not include the effects of the transfer mechanism. In Method 1, the availability of one robot was

determined to be 99.5% (based upon the assumptions presented in the previous chapter). Those processes with other tooling and no robots were estimated to have an availability of 99.9%. Using Equation 6, the robot failure rate was calculated to be 0.121 failures/hour. Next, from Equation 1, the reliability for one robot was calculated to be 38% for a duration of one shift and 14.4% for a duration of one day. Assuming that the processes with other tooling but no robots fail half as frequently as the processes with one or more robots, then the failure rate for those processes is approximately 0.06 failure/hour and the reliability, for one shift and one day respectively, is 61.9% and 38.3%.

## 7.2 Results

<b>Method 1</b>	Station 1	Station 2	Station 3	Station 4	Station 5	<b>System</b>
Availability	99.9%	99.4%	97%	98%	98%	<b>92.5%</b>
Reliability (1 shift)	61.9%	23.5%	3%	2%	2%	<b>0%</b>
Reliability (1 day)	38.3%	5.5%	0%	0%	0%	<b>0%</b>
<b>Method 2</b>	Station 1	Station 2	Station 3	Station 4	Station 5	<b>System</b>
Availability	99.9%	99.8%	99.4%	99.6%	99.6%	<b>98.3%</b>
Reliability (1 shift)	93.4%	87.2%	66.2%	76%	76%	<b>31.1%</b>
Reliability (1 day)	87.2%	76%	43.9%	57.7%	57.7%	<b>9.7%</b>
<b>Method 3</b>	Station 1 (S)	Station 2 (M)	Station 3 (C)	Station 4 (C)	Station 5 (C)	<b>System</b>
Availability	99.9%	99.5%	99%	99%	99%	<b>96.4%</b>
Reliability (1 shift)	90.8%	61.8%	38%	38%	38%	<b>3.1%</b>
Reliability (1 day)	82.5%	38.1%	14.5%	14.5%	14.5%	<b>0%</b>

**Table 7: Availability and Reliability Summary Information for System 3000**

### Section A

In Method 2, the availability of one robot is 99.9% (based upon the assumptions presented in the previous chapter). Those stations without robots were estimated to have an availability of 99.9%. The failure rate for both one robot and the tooling at one station was calculated to be 0.00858 failures/hour. Assuming an exponential failure distribution and using Equation 1, the reliability for one robot and processes with other tooling was calculated to be 93.4% for a duration of one shift and 87.2% for a duration of one day.

<b>Method 1</b>	Station 6	Station 7	Station 8	Station 9	Station 10	<b>System</b>
Availability	99.9%	99.9%	99.9%	99.9%	99.9%	<b>99.5%</b>
Reliability (1 shift)	14%	38%	38%	38%	38%	<b>2.9%</b>
Reliability (1 day)	2%	14.4%	14.4%	14.4%	14.4%	<b>0%</b>
<b>Method 2</b>	Station 6	Station 7	Station 8	Station 9	Station 10	<b>System</b>
Availability	99.9%	99.9%	99.9%	99.9%	99.9%	<b>99.5%</b>
Reliability (1 shift)	87%	93.4%	93.4%	93.4%	93.4%	<b>66.2%</b>
Reliability (1 day)	76%	87.2%	87.2%	87.2%	87.2%	<b>43.9%</b>
<b>Method 3</b>	Station 6 (M)	Station 7 (C)	Station 8 (C)	Station 9 (S)	Station 10 (M)	<b>System</b>
Availability	99.5%	99%	99%	99.9%	99.5%	<b>96.9%</b>
Reliability (1 shift)	61.8%	38%	38%	90.8%	61.8%	<b>5.0%</b>
Reliability (1 day)	38.1%	14.5%	14.5%	82.5%	38.1%	<b>0.3%</b>

**Table 8: Availability and Reliability Summary Information for System 3000**

**Section B**

The Method 3 calculations are completed based on the mini-system estimate presented in Table 6 where the availability for a simple, moderate, and complex mini-system is 99.9%, 99.5%, and 99% respectively. The corresponding failure rates resulted in the following reliability values for each of the three classes of mini-system:

- simple - 90.8% for a duration of one shift and 82.5% for a duration of one day
- moderate - 61.8% for a duration of one shift and 38.1% for a duration of one day
- complex - 38% for a duration of one shift and 14.5% for a duration of one day.

Stations 1, 9 and 11 were classified as simple; Stations 2, 6, and 10 were categorized as moderate; and Stations 3,4,5,7, and 8 were categorized as complex. The transfer processes were categorized as moderate.

Table 9 summarizes the floor pan / underbody subsystem availability at various stages of the process for the three methods previously discussed. The availability is calculated for Branches 1-10 (as labeled in Figure 19) with Branch 10 being the resulting output of the entire system. The three methods yield results ranging from a system availability of 95.8% to 88%. Even the most optimistic case, Method 2, would not result in very promising result for the entire underbody assembly systems or the body shop as a whole. If availability analysis of the remaining five underbody subsystems yielded similar results, then the resulting availability for a six component serial system is approximately 77%. However, this number would be offset by the ability to build buffer stock in between the six subsystems.

Reliability was not further analyzed beyond the reliability block diagram analysis of Sections A and B, because the resulting values would approach zero for the entire floor pan / underbody subsystem.

The pessimistic result of this reliability and availability analysis is evidence of the need to more carefully develop ways in which to accurately assess and validate equipment performance. Reliability analysis at the system level may not be very useful in this

scenario since very detailed failure data is not available and gross estimates are made. The resulting system reliability values that approach zero may indicate that while system reliability is important, in a large complicated system, it is very difficult to achieve consistently high reliability measures over a long period of time. Therefore, a more appropriate and relevant measure may be availability which indicates the percentage of time that equipment is successfully operating over a long period of time. Also, this measure is useful because it considers both reliability and maintainability, two issues that significantly effect equipment performance.

Branch Number	Availability Formula	Availability Value		
		M1	M2	M3
1	$A_A$	92.5%	98.3%	96.4%
2	$A_B$	99.5%	99.5%	96.9%
3	$(A_A \times A_D)$	92%	98.1%	95.9%
4	$(A_B \times A_E)$	99%	99.3%	96.4%
5	$A_C$	99.9%	99.9%	99.9%
6	$(A_A \times A_D) \times (A_B \times A_E)$	91.1%	97.4%	92.4%
7	$(A_B \times A_E) \times (A_C)$	98.9%	99.2%	96.3%
8	$(A_A \times A_D \times A_B \times A_E) \times (A_F)$	90.6%	96.8%	91.9%
9	$(A_B \times A_E \times A_C) \times (A_G)$	98.4%	99%	95.8%
10	$(A_A \times A_D \times A_B \times A_E \times A_F) \times (A_B \times A_E \times A_C \times A_G)$	89.2%	95.8%	88%

**Table 9: Floor Pan / Underbody Availability Values**

While this analysis may not be the most accurate way to determine and predict equipment performance, it can be very useful for analyzing and detecting weak links or vulnerable elements of the system. Additionally, it can be a very useful tool for developing reliability or availability targets early in the design process. One appropriate application for this type of tool is to utilize it to enhance the understanding of the dynamics and

interactions of the system being studied. A better understanding of the system will allow well informed design decisions and tradeoffs to be made throughout the development process.



## 8. Conclusions

### 8.1 Key Learnings

This section will include a brief synopsis of some of the major lessons learned about Chrysler's general approach to developing and operating manufacturing systems with specific references to the minivan platform.

- *Technology alone will not cure equipment performance problems*

Great technical strides have been made with the design of the NS body assembly tooling. However, this enhanced technical capability will not be sufficient by itself to achieve the optimistic 95% uptime goals in the body shop. As discussed later in this section, the number of other factors that influence how the equipment performs is too significant to be ignored. Technical capability is merely one of the many factors that has to be effectively managed in order to achieve the desired equipment performance goals.

- *Teams, groups, organizations need to speak the same language in order to effectively communicate*

The combination of Chrysler's platform organization and the significant amount of external supplier involvement requires that a great deal of team work, coordination, and communication occur. This task is greatly impeded when all involved don't share a common way of discussing and understanding issues. For example, if 10 various parties were asked how they would specifically measure 95% uptime in the body shop, the result is likely to be 10 different answers. This has serious implications, especially when the misunderstanding and miscommunication occur between Chrysler and its vendors who should be evaluated partially on whether or not they delivered the 95% uptime performance that was guaranteed. Unless this communication gap is filled and, some common terms and meanings are explicitly defined, this lack of common understanding will deteriorate relationships and potentially lead to unnecessary and unproductive finger-pointing.

- ***Developing an integrative and comprehensive maintenance strategy is critical to understanding and enhancing equipment performance***

Maintenance strategies can no longer be an afterthought. In order to effectively optimize equipment performance, maintenance will need to be integrated into the overall operating strategy. The costs and benefits associated with various maintenance policies, whether they be proactive or reactive, need to be thoroughly understood so that informed decisions can be made. All equipment is not created equally, and is not of equal importance to the production system. Therefore, the maintenance strategy needs to consider the criticality of the equipment in order to allocate resources, particularly when they are being drawn from a very limited pool.

- ***A common, well-defined measurement system in conjunction with concise goals is a must for assessing equipment performance and the effectiveness of various programs***

Much observation and analysis revealed a lack of well-defined and commonly understood metric systems. This revelation is crucial because in order to track progress toward any goal, there must be in place, some scheme for measuring the progress. Additionally, all that are involved with the process in question, must be able to easily see and understand how their roles directly impact the goals. For example, in both the Windsor and St. Louis assembly plants, it was noticed that although some downtime data was tracked, there seemed to be no rigorous system in place to systematically track, analyze, measure improvement then share the resulting information throughout the body shop.

- ***Simulation studies, as conducted, are not reliable indicators of equipment performance***

Some of the computer simulation studies done for the NS body shop equipment stated that the purpose was to “assist in the systems evaluation and validation process,” “to assess system performance under a variety of conditions,” and to “determine net/gross throughput potential.” The assertion that these models and studies can be used to validate processes, assess equipment performance, or determine throughput potential is dangerous

for two reasons. First, such simulations are very sensitive to input data which needs to be extremely accurate in order to generate reliable results. Secondly, many factors that influence equipment performance can not be accurately modeled into a computer simulation. In many instances, it was noted that data used as inputs were estimates and could not be verified as highly accurate. Specific examples include inaccurate and/or incomplete data for repair times, failure frequency, and robot reliability.

Nevertheless, simulation could play a very important role in the design process when used in the proper context. Given the two aforementioned difficulties with computer simulation, the purpose of a simulation study should not be to act as a validation tool after a design has been chosen, but rather it should be used early in the design process as a means to compare several potential design solutions. Given that several factors cannot be modeled and accurate data is not readily available, the powers of simulation lie in its ability to serve as a process comparison tool as opposed to a process validation tool.

- ***Several factors effect equipment performance, many hard to quantify***

Below is a list of the key factors that influence equipment performance in the body shop:

1. design, build and installation of the equipment
2. operator/equipment interaction
3. Chrysler/supplier interaction
4. completion of routine maintenance
5. operating conditions
6. plant atmosphere (i.e. dirt, humidity, heat, etc.)
7. product quality
8. continuos improvements efforts

Although the effects of most of these factors are rather apparent, what is not so clear nor simple is the nature in which these effects are compounded due to the fact that many of the factors are interdependent and heavily intertwined.

- ***Many opportunities exist to increase organizational learning among various Chrysler organizations and its equipment suppliers.***

The NS equipment development process created a great number of opportunities for knowledge sharing and information exchange to occur, not only among the minivan platform and the equipment suppliers, but also among different suppliers, as well as among various other groups and platforms within Chrysler. Electronic connections are being established so that customer and supplier can create an ongoing feedback loop with regards to equipment performance. Internal learning among advance manufacturing engineering groups will be further enhanced due to a recent reorganization which left all advance manufacturing engineering groups reporting to the same organization. Finally, an opportunity exists between the St. Louis and Windsor assembly operations to learn how different operating conditions and organizational structures impact equipment performance. The two sets of “identical” equipment will be operating in two different environments under varying operating conditions. This situation presents an excellent opportunity for further research and analysis of factors effecting equipment performance.

- ***While Chrysler benefits tremendously from its current equipment acquisition policies, there is a potential downside to these policies.***

Chrysler’s equipment acquisition strategies work well for several reasons. The increased knowledge base from pooled resources and skills is beneficial to all involved. When Chrysler participates in repeated open information exchanges with its suppliers, transactions become more efficient since some level of familiarity with people and processes is developed. The costs and risks of investments and process innovations are shared among the various suppliers, as well as other auto manufacturers. Nevertheless, there are some potentially big losses that could be associated with this current equipment acquisition system. Chrysler could become too dependent on suppliers to provide process knowledge, potentially losing its own expertise. Also, since suppliers, who are usually hit extremely hard during downturns in the auto industry, will probably have a tougher time than Chrysler trying to survive economic fluctuations, Chrysler could be left in a

very vulnerable position during the next downturn. Finally, because no unified strategy has emerged as of yet with regards to developing process equipment, many of the efficiencies that could be gained from repeated transactions are hindered.

## **8.2 Recommendations**

Below is a brief list of some recommendations resulting from the research conducted thus far.

- Enhance the design process with simulation
- Develop a system of measurements to evaluate processes and programs
- Transform information overload into meaningful measurements
- Foster cultural change in the plants to increase the likelihood of success for PM and other programs
- Use plant/manufacturing experience to complement hard data and facts
- Focus on collecting accurate data for
  1. computer simulation input data in order to gain full benefits of simulation
  2. thorough internal tracking of equipment performance

## **8.3 Future Research**

Many issue related to equipment performance are still not well understood. For whatever reasons, there has not been a tremendous amount of research focused on large process systems such as those found in automobile body shops. Additionally, the research that has been conducted regarding reliability, especially of mechanical systems, is sporadic and yields results that may not be applicable to other systems. With this in mind, to truly create an optimal plan for evaluating equipment performance and to understand the factors effecting equipment performance, there exists a need to conduct more field research of systems that are in service. Some possible topics of interest that can be investigated include developing data collection systems and failure reporting systems which can be used to assess and evaluate equipment performance. Also, these systems can facilitate studies to determine how well reliability prediction and estimation

techniques correlate to in service reliability. Another area to investigate further is completing a cost analysis of various maintenance policies and developing a system for allocating maintenance resources.

## Appendix A

### PM Time Requirements for Electrician

*all times are in hours*

	Break	Lunch	Weekend	Totals
<b>Daily</b>	0.00	0.00	0.00	0.00
<b>Weekly</b>	0.00	0.00	0.00	0.00
<b>Monthly</b>	16.00	9.31	19.51	44.82
<b>Semi-Annually</b>	0.59	0.25	1.00	1.84
<b>Annually</b>	2.95	6.16	44.60	53.71

### Annual PM Time Requirements for Electrician

*all times are in hours*

	Break	Lunch	Weekend	Totals
<b>Daily</b>	0.00	0.00	0.00	0.00
<b>Weekly</b>	0.00	0.00	0.00	0.00
<b>Monthly</b>	192.00	111.72	234.12	537.84
<b>Semi-Annually</b>	1.18	0.50	2.00	3.68
<b>Annually</b>	2.95	6.16	44.60	53.71
<b>Totals</b>	196.13	118.38	280.72	<b>595.23</b>

### Daily PM Time Requirements for Electrician

*all times are in hours*

	Break	Lunch	Weekend	Totals
<b>Daily</b>	0.000	0.000	0.000	0.00
<b>Weekly</b>	0.000	0.000	0.000	0.00
<b>Monthly</b>	0.526	0.306	0.641	1.47
<b>Semi-Annually</b>	0.003	0.001	0.005	0.01
<b>Annually</b>	0.008	0.017	0.122	0.15
<b>Totals</b>	0.54	0.32	0.77	<b>1.63</b>

**PM Time Requirements for Millwright**

*all times are in hours*

	<b>Break</b>	<b>Lunch</b>	<b>Weekend</b>	<b>Totals</b>
<b>Daily</b>	0.00	0.00	0.00	0.00
<b>Weekly</b>	1.17	1.33	0.00	2.50
<b>Monthly</b>	0.51	4.31	11.92	16.74
<b>Semi-Annually</b>	0.17	2.33	11.16	13.66
<b>Annually</b>	0.00	0.00	4.00	4.00

**Annual PM Time Requirements for Millwright**

*all times are in hours*

	<b>Break</b>	<b>Lunch</b>	<b>Weekend</b>	<b>Totals</b>
<b>Daily</b>	0.0	0.0	0.0	0.0
<b>Weekly</b>	58.5	66.5	0.0	125.0
<b>Monthly</b>	6.1	51.7	143.0	200.9
<b>Semi-Annually</b>	0.3	4.7	22.3	27.3
<b>Annually</b>	0.0	0.0	4.0	4.0
<b>Totals</b>	65.0	122.9	169.4	357.2

**Daily PM Time Requirements for Millwright**

*all times are in hours*

	<b>Break</b>	<b>Lunch</b>	<b>Weekend</b>	<b>Totals</b>
<b>Daily</b>	0.000	0.000	0.000	0.0
<b>Weekly</b>	0.160	0.182	0.000	0.3
<b>Monthly</b>	0.017	0.142	0.392	0.6
<b>Semi-Annually</b>	0.001	0.013	0.061	0.1
<b>Annually</b>	0.000	0.000	0.011	0.0
<b>Totals</b>	0.2	0.3	0.5	1.0



**PM Time Requirements for Pipefitter**

*all times are in hours*

	<b>Break</b>	<b>Lunch</b>	<b>Weekend</b>	<b>Totals</b>
<b>Daily</b>	0.08	0.00	0.00	0.08
<b>Weekly</b>	0.16	0.25	0.00	0.41
<b>Monthly</b>	4.41	5.56	5.51	15.48
<b>Semi-Annually</b>	0.34	0.00	0.00	0.34
<b>Annually</b>	0.00	0.00	0.00	0.00

**Annual PM Time Requirements for Pipefitter**

*all times are in hours*

	<b>Break</b>	<b>Lunch</b>	<b>Weekend</b>	<b>Totals</b>
<b>Daily</b>	24.0	0.0	0.0	24.0
<b>Weekly</b>	8.0	12.5	0.0	20.5
<b>Monthly</b>	52.9	66.7	66.1	185.8
<b>Semi-Annually</b>	0.7	0.0	0.0	0.7
<b>Annually</b>	0.0	0.0	0.0	0.0
<b>Totals</b>	85.6	79.2	66.1	<b>230.9</b>

**Daily PM Time Requirements for Pipefitter**

*all times are in hours*

	<b>Break</b>	<b>Lunch</b>	<b>Weekend</b>	<b>Totals</b>
<b>Daily</b>	0.066	0.000	0.000	0.1
<b>Weekly</b>	0.022	0.034	0.000	0.1
<b>Monthly</b>	0.145	0.183	0.181	0.5
<b>Semi-Annually</b>	0.002	0.000	0.000	0.0
<b>Annually</b>	0.000	0.000	0.000	0.0
<b>Totals</b>	0.2	0.2	0.2	<b>0.6</b>

### PM Time Requirements for Toolmaker

*all times are in hours*

	Break	Lunch	Weekend	Totals
<b>Daily</b>	4.06	0.00	0.00	4.06
<b>Weekly</b>	15.93	9.46	8.99	34.38
<b>Monthly</b>	14.66	8.39	19.90	42.95
<b>Semi-Annually</b>	0.00	0.00	0.00	0.00
<b>Annually</b>	0.00	0.00	0.00	0.00

### Annual PM Time Requirements for Toolmaker

*all times are in hours*

	Break	Lunch	Weekend	Totals
<b>Daily</b>	1218.0	0.0	0.0	1218.0
<b>Weekly</b>	796.5	473.0	449.5	1719.0
<b>Monthly</b>	175.9	100.7	238.8	515.4
<b>Semi-Annually</b>	0.0	0.0	0.0	0.0
<b>Annually</b>	0.0	0.0	0.0	0.0
<b>Totals</b>	2190.4	573.7	688.3	<b>3452.4</b>

### Daily PM Time Requirements for Toolmaker

*all times are in hours*

	Break	Lunch	Weekend	Totals
<b>Daily</b>	3.34	0.00	0.00	3.3
<b>Weekly</b>	2.18	1.30	1.23	4.7
<b>Monthly</b>	0.48	0.28	0.65	1.4
<b>Semi-Annually</b>	0.00	0.00	0.00	0.0
<b>Annually</b>	0.00	0.00	0.00	0.0
<b>Totals</b>	6.0	1.6	1.9	<b>9.5</b>

### PM Time Requirements for Welder Repair

*all times are in hours*

	Break	Lunch	Weekend	Totals
<b>Daily</b>	58.16	8.46	8.00	74.62
<b>Weekly</b>	7.22	4.15	0.50	11.87
<b>Monthly</b>	115.70	38.04	55.02	208.76
<b>Semi-Annually</b>	8.81	7.84	0.33	16.98
<b>Annually</b>	15.53	22.97	90.71	129.21

### Annual PM Time Requirements for Welder Repair

*all times are in hours*

	Break	Lunch	Weekend	Totals
<b>Daily</b>	17448.0	2538.0	2400.0	22386.0
<b>Weekly</b>	361.0	207.5	25.0	593.5
<b>Monthly</b>	1388.4	456.5	660.2	2505.1
<b>Semi-Annually</b>	17.6	15.7	0.7	34.0
<b>Annually</b>	15.5	23.0	90.7	129.2
<b>Totals</b>	19230.6	3240.6	3176.6	<b>25647.8</b>

### Daily PM Time Requirements for Welder Repair

*all times are in hours*

	Break	Lunch	Weekend	Totals
<b>Daily</b>	47.80	6.95	6.58	61.3
<b>Weekly</b>	0.99	0.57	0.07	1.6
<b>Monthly</b>	3.80	1.25	1.81	6.9
<b>Semi-Annually</b>	0.05	0.04	0.00	0.1
<b>Annually</b>	0.04	0.06	0.25	0.4
<b>Totals</b>	52.7	8.9	8.7	<b>70.3</b>

## **Appendix B**

### **Floor Pan / Underbody Assembly - NS System 3000**

#### ***Description of Operations***

##### **Station 1**

Auto load - places underbody (from 2960)  
Lifter raises  
Transfer - to station 2

##### **Station 2**

Receive underbody from station 1  
Engage station 2 tooling  
Floor pan conveyor - feeds MHR  
Material handling robot - loads floor pan  
Lifter raises  
Transfer - to station 3

##### **Station 3**

Receive underbody from station 2  
Engage station 3 tooling  
Engage six welding robots  
Lifter raises  
Transfer - to station 4

##### **Station 4**

Receive underbody from station 3  
Engage station 4 tooling  
Engage four welding robots  
Lifter raises  
Transfer - to station 5

##### **Station 5**

Receive underbody from station 4  
Engage station 5 tooling  
Engage four welding robots  
Lifter raises  
Transfer - to station 6

##### **Station 6**

Receive underbody from station 5  
Engage station 6 tooling

##### **Station 6 (cont'd)**

Engage two welding robots  
Overhead transfer - to station 7

##### **Station 7**

Receive underbody from station 6  
Engage station 7 tooling  
Engage pierce units  
Conveyors - remove slugs  
Overhead transfer - to station 8

##### **Station 8**

Receive underbody from station 7  
Engage station 8 tooling  
Engage pierce units  
Conveyors - remove slugs  
Overhead transfer - to station 9

##### **Station 9**

Receive underbody from station 8  
Manually load seat strikers  
Overhead transfer - to station 10

##### **Station 10**

Receive underbody from station 9  
Manually load nuts  
Engage spindle units  
Overhead transfer - to station 10

##### **Station 11**

Receive underbody from station 10  
Auto unload - places underbody (to 3050)

### **3000 System Description**

1. Automatic loader moves underbody from 2960 to main line. Lift and carry transfer to station 2.
2. Operator manually load skin (floor pan) with the assistance of an articulating arm onto short conveyor. Conveyor feeds into main line where a Nachi material handling robot loads the floor pan onto the underbody on the main line. Lift and carry transfer to station 3.
3. Six Nachi robots perform welding operations. This station is where the geometry for the underbody is set. Lift and carry transfer to station 4.
4. Four Nachi weld robots perform welding operations. Lift and carry transfer to station 5.
5. Four Nachi weld robots perform welding operations. Lift and carry transfer to station 6.
6. Two Nachi weld robots perform welding operations. Overhead transfer to station 7.
7. Piercing unit cuts holes in underbody so that seat strikers (dog bones) can be bolted on. Conveyor catches slugs and feed them to a collection area outside the system. Overhead transfer to station 8.
8. Piercing unit cuts holes in underbody so that dog bones can be bolted on. Conveyor catches slugs and feed them to a collection area outside the system. Two hydraulic units power both systems and one backup unit is also available. Overhead transfer to station 9.
9. Operator manually loads dog bones. Overhead transfer to station 10.
10. Operator manually loads nuts in automatic nut runner (spindle unit). Overhead transfer to station 11.
11. Automatic unloader moves underbody to conveyor to 3050 (underbody respot).

#### **Other miscellaneous notes about System 3000**

- Cymonic drive between stations 4 & 5
- Piercing units powered by two hydraulic units one backup unit is standing by
- No clamps are on the station 10 tooling,
- the ISI overhead has clamps on the transfer tooling

- 5 separate transfer units - 1st 3 and last 2 appear to be joined; all might act synchronously

The lift and carry operations consists of the lifter performing the following functions:

1. raise
2. advance
3. lower
4. return

## Bibliography

- Blache, Klaus M. and Anil B. Shrivastava, "Defining Failure of Manufacturing Machinery and Equipment," *Proceedings Annual Reliability and Maintainability Symposium*, 1994, pages 69-75.
- Brall, Aron, "A Model for Success in Implementing an R&M Program by a Supplier of Manufacturing Machinery," *Proceedings Annual Reliability and Maintainability Symposium*, 1994, pages 59-64.
- Carter, A. D. S, *Mechanical Reliability*, Macmillan, London, 1986.
- Chrysler, Detroit Center Tool, Progressive Tool and Industries, Co., Field Interviews, 1994.
- Davidson, John, *The Reliability of Mechanical Systems*, The Institution of Mechanical Engineers, London, 1988.
- Fine, Charles, MIT Sloan School of Management Lecture on Process Equipment, April 10, 1995.
- Fine, Charles, Nitin Joglekar, and Geoffrey Parker, "Models of Process Equipment Development: Findings from the Automotive Assembly Tooling Industry," Working Paper, MIT Sloan School of Management, 1994.
- Kapur, K. C. and L. R. Lamberson, *Reliability in Engineering Design*, John Wiley and Sons, New York, 1977.
- Kindree, Jack D., Raymond R. Melton, Harold E. Raffa, and Robert J. Reynolds, "An Overview of an R&M Guideline for Manufacturing Machinery and Equipment," *Proceedings Annual Reliability and Maintainability Symposium*, 1994, pages 65-68.
- Morton, Donald A, "Reliability-Centered Maintenance: The Wave of the Present," *AIPE Facilities*, September/October 1994, pages 27 - 31.
- Murry, Robert J. and Billy F. Mitchell, "Cost Savings from a Practical Predictive-Maintenance Program," *Proceedings Annual Reliability and Maintainability Symposium*, 1994, pages 206-209.
- Nakajima, Seiichi, *Introduction to TPM*, Productivity Press, Cambridge, 1988.
- Pecht, Michael, "Reliability Predictions: Their Use and Misuse," *Proceedings Annual Reliability and Maintainability Symposium*, 1994, pages 386-389.

Rao, Singiresu S., *Reliability-Based Design*, McGraw-Hill, New York, 1992.

Rooney, John Peter, "Customer Satisfaction" *Proceedings Annual Reliability and Maintainability Symposium*, 1994, pages 376-381.

Voigt, Ed, "TPM for the Real World," *The Maintenance Journal*, September/October 1994, pages 14-21.

Whitney, Daniel, MIT Sloan School of Management Lecture on Make/Buy Strategies, April 19, 1995.

Wood, Alan P. and Jon G. Elerath, "A Comparison of Predicted MTBFs to Field and Test Data," *Proceedings Annual Reliability and Maintainability Symposium*, 1994, pages 153-156.

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