Reliability/Availability of Manufacturing Cells and Transfer Lines

by

Balaji Kannan

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Approved by

JT. Black, Co-chair, Professor Emeritus of Industrial & Systems Engineering
Saeed Maghsoodloo, Co-chair, Professor Emeritus of Industrial & Systems Engineering
Amit Mitra, Professor of Management

Thesis Abstract

One of the major wastes in a manufacturing system is downtime caused by machine breakdown/failure and the time and cost incurred to repair the failed machine. Machine breakdown leads to stoppage of production in manufacturing cells and automated serial production lines (Transfer lines) until the machine is brought back to operable condition. Obtaining the reliability/availability measures of machines in manufacturing systems is necessary to schedule preventive maintenance and periodic replacement of critical components in order to increase manufacturing uptime. To assess the reliability measures and availability of manufacturing cells and transfer lines, field failure data were collected from a crankshaft manufacturing cell and an automated transfer line and were fitted to relevant statistical distributions using Goodness of fit tests, and the necessary reliability and availability measures were obtained using Maximum likelihood estimation (MLE). The results were that the time between failures of CNC machines and Transfer Lines follows the Weibull distribution (in most cases) and Transfer Lines require higher maintenance requirements than manufacturing cells.

Table of Contents

List of Tables

List of Figures

List of Notations and Acronyms

t – Mission time

T – Time between failures

f(t) – Failure density function of T at time t

F(t) =Q(t) = Cumulative density function (cdf) of T or cumulative failure probability by time t

or the unreliability function by time t

$R_i(t)$ – Reliability of the i^{th} component/machine tool

$R_{SYS}(t)$ – Reliability of the system/ Manufacturing cell

$h_i(t)$ – Failure rate/ hazard function of the i^{th} component/ machine tool

$h_{sys}(t)$ – Hazard function of the system/ manufacturing cell

$H_i(t)$ – Cumulative hazard function of the i^{th} machine tool

$H_{sys}(t)$ – Cumulative hazard function of the system/ manufacturing cell

TBF – Time between failures

$MTBF_i$ – Mean time between failures of the i^{th} machine tool

$MTBF_{sys}$ – Mean time between failures of the system/manufacturing cell

MLE – Maximum likelihood estimate

WIP – Work In Process Inventory

CNC – Computer Numerical Control

CHAPTER 1

Introduction

Reliability is one of the most important characteristics of components, products, and large complex systems. Manufacturing can be defined as the process of converting materials from one form to the form that customer's desire. Products are manufactured according to customer or design specifications. Quality of a manufacturing company can be measured by the organizations ability to produce defect-free, reliable components or products. Defect is a smaller the better (STB) type quality measure. Reliability also has a great effect on the consumers' perception of manufacturer. Consumers' experiences with recalls, repairs and warranties will affect the future sales of a manufacturer.

The ability of a manufacturer to produce reliable components depends on system reliability. Reliability of a system is dependent on the reliability of individual components. A manufacturing system is an integration of machines, materials, humans, material handling devices and computers. Then, for a manufacturing system to be reliable all the above mentioned components must be reliable. Machines are the most important component in a manufacturing system. Machines can be a simple tool such as a lathe, drilling machine, etc. or a highly automated transfer line or a flexible manufacturing system depending on the functional requirements of the manufacturing system. Regardless of the type of machines used by a manufacturing system, all machines must be reliable to accomplish a task.

The unplanned or unscheduled time period for which needed machines are unavailable for production is called downtime. Machine failures may occur due to a variety of reasons such as fatigue, aging, wear out, excessive stress, vibrations, operator error, etc. Machine failures can be broadly classified as mechanical, electrical and hydraulic/pneumatic. Machine failures are undesirable in manufacturing. Unreliability/Unavailability can lead to the following manufacturing wastes.

(1) **Waiting** – Unavailable machines cause waiting and underutilization of machines and operators. Waiting is a non-value added activity and poor machine availability leads to waiting and in some cases may even halt the entire production in a factory. Delay of the downstream production when delay on upstream manufacturing cell causes kanban link to dry up.

(2) **Not utilizing people** – When machines fail it needs to be repaired or replaced, and until it gets repaired, operators need to wait. This is uneconomical and leads to the waste of not utilizing people properly.

(3) **Wasted Motion & Excessive Transportation** – When a machine fails, sometimes it is replaced with another similar machine and this involves wasted motion and excessive transportation.

(4) **Inventory** – One approach in dealing with process and machine unreliability is to allocate buffers. This leads to excess unnecessary WIP which is a non-value added activity.

(5) **Extra Processing** – When a machine or component fails it needs to be repaired or replaced. Unlike maintenance, repair is an unplanned/unscheduled activity and causes delay and extra processing which requires additional labor, material and other resources.

To avoid unplanned downtime, the availability of machines in a manufacturing system should be maximized. 100% availability can never be obtained in a manufacturing setting, but knowledge of failure distributions, failure rates and the MTBF of the machines can be helpful in scheduling preventive or predictive maintenance, and periodic replacement of critical components in the machines which can prevent or minimize unplanned downtime.

CHAPTER 2

Literature Review

Ebeling (1997) defines Reliability as the probability that a component (or) equipment will perform a required function for a given period of time when used under stated operating conditions. This definition by Ebeling is widely accepted in engineering. However in the area of manufacturing the term Availability is a more common measure of equipment performance than the reliability function. Groover (2000) claims that the term availability is especially appropriate for automated production equipment. The Dictionary of Engineering (2003) defines availability as “The quality of being at hand when needed”. Another qualitative definition of availability is given by Blanchard (1997) as “A measure of the degree of a system which is in operable and committable state at the start of a mission when the mission is called for at an unknown point in time”. This definition may not be applicable in a manufacturing environment. In particular, the phrase “unknown point in time” is not very well suited in a manufacturing setup because in a manufacturing environment the availability of a machine or equipment is generally planned or scheduled. In manufacturing, the availability is generally expressed by either time interval or by the downtime of the system. The time interval definition of availability is given by Groover (2000) who uses two reliability terms, Mean time between failure (MTBF) and Mean time to Repair (MTTR), where MTBF indicates the average length of time the an equipment runs between breakdowns. The MTTR indicates the average time required to service the equipment and put it back into operation when a breakdown occurs. Then availability can be represented quantitatively as MTBF/(MTBF+MTTR). If downtime is used to express reliability, then reliability could be defined as the probability of not having a downtime for a specified time interval (usually within the warranty period).

There are several definitions for the term system. The dictionary of Engineering defines a system as a group of interacting, interrelated or independent elements forming a complex whole. The general definition of reliability could be extended to the systems, and system reliability can be defined as the probability that the entire system (Hardware, Software, Personnel, etc.) would perform the required functions satisfactorily in a specified environment. Kapur and Lamberson (1985) define the reliability of a system as the probability that the system will adequately perform the intended function under the stated environmental conditions for a specified interval of time. Dhillon (1983) subdivides the system reliability into two broad categories, i.e. design reliability and operational reliability. Design reliability can be defined as designing a system to have high reliability. Ebeling notes that reliability by design is an iterative process that begins with the specification of reliability goals consistent with cost and performance objectives. Operational reliability is concerned with failure analysis, repairs, maintenance, preventive maintenance and so on.

Before reviewing the literature on Manufacturing Systems, a clear definition of manufacturing systems is necessary. Black (2003) defines manufacturing systems as “Complex arrangement of physical elements characterized and controlled by measurable parameters”. The term measurable parameters is different for different types of manufacturing systems, but some of the general measurable parameters that are vital to all manufacturing systems are work in process (WIP), production rate, throughput time and quality of the manufactured product. Hon (2005) conducted a detailed survey of the performance measures for manufacturing systems that were most widely used by companies and are ranked as follows: cost, quality, productivity, time and flexibility. One of the measurable parameter that characterizes any manufacturing system is its reliability.

There are numerous papers that discuss the methodology of forming manufacturing cells through mathematical and simulation models. Group technology is one technique where dissimilar machines are grouped together to form manufacturing cells. Parts of similar size and geometry can often be processed by a single set of processes. Hyer and Brown (1995) define manufacturing cells as "Dedicating equipment, and materials to a family of parts or products with similar processing requirements by creating work flow where tasks and those who perform them are closely connected in terms of time, space and information". Black (2003) provides a simpler definition of manufacturing cells. A part family based on manufacturing processes type would have the same sequence of manufacturing processes. The set of processes is arrayed to form a cell. The academic research uses various mathematical methods to identify part families and form manufacturing/machining cells. Some of the approaches are listed below:

Descriptive Methods: Production flow analysis (PFA) proposed by Burbidge, component flow analysis (CFA) by El-Essawy and Torrance and production flow synthesis by De Beer and De Witte. All of the above mentioned methods form manufacturing cells by using the production planning data entered in the route sheets. Therefore, a drawback of these methods is that it assumes the accuracy of existing route sheets, with no consideration given to whether those process plans are up-to-date or optimal with respect to the existing mix of machines.

Array-Based Methods/ Similarity coefficient methods: Rank order clustering (ROC) algorithm developed by King (1981), ROC2 algorithm enhanced by King and Narkornchai (1982), Matrix clustering methods by Narendran and Srinivasan (1999), direct clustering algorithm developed by Chan and Milner (2002), clustering approach developed by McAuley (1995) and graph theoretic approach developed by Rajagopalan and Bathra (1999). Furthermore there are analytical approaches that use mathematical programming such as the method proposed by Purcheck (2003). All the above mentioned methods are computationally complex and might require a software program to execute the algorithm. Another failure of the group technology method is that it ignores people.

A recent survey conducted by Olorunniwo and Udo (2005) in the US manufacturing sector shows that cell formation practices in the industry depend mainly on judgment, experience and familiarity with part/machine spectrum. This result makes the manufacturing cell definition by Black mentioned previously the most appropriate and applicable in the industries.

The advantages and the disadvantages of cells have been thoroughly researched. The tangible advantages of manufacturing cells are due mainly to the proximity of all machines required to make the family of parts (Wemmerlov and Hyer). This reduces the total distance that must be traveled by the batches of parts in the family. This in turn reduces the average work-in-process levels of the pats as well as subassemblies in which they are used. Other advantages of cells include Setup time reduction (Shingo), JIDOKA (Ohno), i.e. autonomous control of quality and quantity and higher worker motivation and job satisfaction (Black). Some disadvantages of cells mentioned in the literatures are increased investment (Vakharia), low machine utilization (Bulbridge) and lack of flexibility in presence of machine breakdown (Seifoddini and Djassemi; Parsaei et al).

There is an extensive literature on the design of production lines but the literature on reliability/availability estimation of the production/transfer line is not exhaustive. Freeman

(1964) studied the two and three stage serial lines with constant processing time and exponential machine breakdowns. He made some generalizations about how to allocate buffers in presence of machine breakdowns. A similar work in this field was performed by Conway et al who studied reliable serial lines with exponential and uniform processing time distributions and unreliable workstations subject to exponential breakdowns. Balanced and unbalanced lines with unreliable stations were compared in terms of overall processing times and buffer capacity. They established a set of design rules for buffer allocation for lines having low to moderate coefficient of variation.

A widely used procedure in academia to perform various types of reliability analysis is the Markov method. This method is named after the Russian mathematician, Andrew Andreyevich Markov (1856-1922). Markov models are quite useful in modeling systems with dependent failure and repair modes. Greshwin (1986) et al developed a dynamic discrete time Markov chain model for the serial transfer line with unreliable machines and non-failing buffers. Their model resulted in a Jackson network closed form solution for the line's availability. Their computational results were applicable for the two and three workstation lines with geometrically distributed failure and repair times. Sheskin (1976) used continuous time Markov chain methods to relate the overall line's production rate and buffer storage. His exact results for three and four station lines indicate that there is an increase in production rate for large and equally allocated buffers.

Hassett and Dietrich (1995) proposed a method for computing stationary state workstation model probabilities for unreliable transfer lines. They developed an algorithm to isolate and remove transient states from their model. They also developed a linear regression model to predict the effects of changing individual workstation availabilities and buffer capacities on overall line availability.

Papadopoulos (1999) studied balanced serial transfer lines having exponential and Erlang distributed processing times and exponential service and repair times. His results analyzed the effect of service time distribution, availability of unreliable stations and the repair rate on buffer allocation and throughput.

All the above mentioned papers assume an underlying failure and repair time distribution and suggest allocating buffers to handle machine breakdowns. But none actually determine or suggest a model to determine the failure and repair distributions of transfer lines. Also all the above papers provide the generalized results for transfer lines with two, three or four work stations and their results cannot be generalized for the transfer lines having 10 or 15 stations which are very common in the automotive manufacturing industries.

The reliability estimation of the manufacturing system is relatively new in the literature. Adamyan and He (2002) suggested ways of assigning probability to failure occurrences in manufacturing systems using sequential failure analysis. Their claim was that the reliability and safety of manufacturing systems depend not only on the failed states of system components, but also on the sequence of occurrence of those failures. Their method involved Petri Net modeling for the assessment of reliability and safety of manufacturing systems. They applied their model to assess the reliability and safety of an automated machining and assembly system consisting of one machine station and one robot. The problem with the above approach is that the reliability determined through Petri Nets involved graphing and construction of reachability trees and when the number of components in a system increases the construction of reachability trees becomes a tedious task and may require specific software program for the construction of such complex trees.

There exist an extensive number of papers involving reliability assessment and reliability analysis for highly automated flexible manufacturing systems. Savsar (1998) developed mathematical models to study and compare the operations of a fully reliable and an unreliable flexible manufacturing cell (FMC), each with a flexible machine, a loading/unloading robot and a pallet handling system. The study involved comparing the utilization rate of all the components in a cell (i.e. the machine utilization rate, robot utilization rate and pallet utilization rate) for the reliable and unreliable flexible manufacturing cell. The results concluded that the machine utilization and robot utilization was lower for the unreliable cells even at an increased production volume. The main drawback of this study was that the reliability function of the components had to be inputted into the model and there was no measure of actually calculating (or estimating) the reliability function of the flexible manufacturing system.

The use of probability distribution to represent failures and repairs in a flexible manufacturing system was proposed by Vineyard et al. (1996). Separate data were included for the mechanical, hydraulic, electrical, electronic, software and human failures as well as repairs. The data were fitted to appropriate probability distributions. Their study indicated that the time between failures follows a Weibull distribution and the time to repair follow lognormal distribution. The conclusion of the above research was that electronic components were the least likely to fail but the mechanical failures resulted in the highest downtime. Another conclusion of the study was that the contribution of human failures, i.e. failures due to human errors was the most significant contributor to the total failure categories indicating that the increased complexity of the flexible manufacturing systems might lead to more human errors.

Many papers (Wemmerlov and Johnson (1997), Askin and Estrada (1999), Wemmerlov and Hyer (1989), Hunter (2001), Agarwal and Sarkis (1998)) have compared the Lean/Cellular manufacturing to the functional/job shop layout and have discussed the advantages of cellular layout such as the reduction of WIP, reduction of the throughput times, reduction of setup times and better ergonomics to name a few. But all the above mentioned papers fail to consider the reliability of machine tools/ manufacturing cells in their analysis.

Jeon et al (1998) states that machine failures should be considered during designing of cellular manufacturing systems to improve the overall performance of a system. Their study included the consideration of machine failure for determining part families and formation of manufacturing cells. They used similarity coefficient approach based on alternative routes during machine failure and generated the similarity matrix using C programming. But the above paper failed to consider the scheduling problem if the alternative routes are occupied and also their analysis did not consider the production rates of manufacturing cells. A limited number of studies are available that take into account reliabilities in their comparison of functional and the cellular layout (Seifoddini and Djassemi (2001), Logendran and Talkington)

Seifoddini and Djassemi (2001) compared the performance of cellular manufacturing and job shop manufacturing by taking into account the reliability of machines. They used simulation modeling for their analysis. Their results showed that cellular manufacturing outperformed job shop manufacturing in terms of WIP and flow times only at high reliability levels of machines. The study concluded that the performance of cellular manufacturing systems is more sensitive to reliability changes than the performance of job shop systems.

Logendran and Talkington (1997) did a similar study as Seifoddini and Djassemi. The study compared the mean work in process and mean throughput time of cellular and job shop manufacturing in presence of machine breakdown using both simulation modeling and statistical experimental design. Their analysis included a six factor- layouts, demand, run time, material handler, batch size and repair policy – a factorial experiment (2^5*2), representing 32 different scenarios, each with cellular and functional layouts for each of the two performance measures. The conclusion of the research was that in presence of frequent machine breakdowns, the functional layout was better when compared to the cellular layout. But the above results were only relevant for large batch sizes. With smaller batch sizes the cellular layout outperformed functional layout in terms of WIP and throughput time (TPT) even in the presence of unreliable machines/ machine breakdown. But the above paper failed to incorporate the reliability function and the underlying distribution of machine tool failure data in their simulation model as well as their experimental design. Also, they considered the repair policy in their model but failed to consider the time to repair distribution and the mean time to repair for the machines in the functional and the cellular layout.

The amount of research dealing with the reliability aspects of lean manufacturing cells/ manufacturing cells is fairly small.

Das et al (2006) presents a multi objective mixed integer programming model of cellular manufacturing system which minimizes the total system costs and maximizes the machine reliabilities along the selected processing routes. Their proposed approach provides a flexible routing which ensures high overall performance of the cellular manufacturing systems (CMS) by minimizing the total costs of manufacturing operations, machine underutilization and inter-cell material handling. Also they performed a sensitivity analysis of their model on reliability parameters. They studied the effects of the change in failure rates and mean time to repair on the following 5 factors: availability, available time, % utilization, utilized time and non-utilized time. The disadvantage of the above model is that they assumed the failure rates and the repair rates of the machine to be exponentially distributed. But the machine failure is not always exponentially distributed. Their sensitivity analysis would have been more revealing if they had run their above analysis for different failure and repair distributions of the machines. One more disadvantage of the above proposed model is that it focuses more on machine utilization, but in a lean environment the focus should be on worker/operator utilization rather than machine utilization. Similar to the work mentioned above, Jeon et al (1998) and Diallo et al (2001) proposed CMS design approaches which considered alternate routings to handle machine breakdown.

Jeon et al (1998) developed a mixed integer programming model that simultaneously considers scheduling and operational aspects of grouping machines into cells. To improve and maintain cell performance a part can be allocated to available alternative routes in case of machine failure. The study considered a predefined number of breakdowns for each of the machines and developed a model to reduce waiting cost and inventory holding cost by selecting alternative routes to handle machine breakdowns. The above model did not consider either the reliability function or the MTTF of machine tools.

Diallo et al (2001) proposed an approach for designing manufacturing cells in which the process plans can be changed in the presence of machine breakdowns. The study used linear programming approach where the objective was to maximize production volume and the constraints were available machines, a set of process plan, and machine loads. The above method was computation intensive and did not consider the production time delay caused in changing the process plan. One more concern regarding the model is that its objective function is to maximize the production volume. In a lean/cellular manufacturing environment the objective is never maximizing the production volume, which questions the applicability of the model in a lean manufacturing environment.

One of the well accepted practice to improve the reliability of any system is redundancy, i.e. having a buffer. Gupta and Kavusturucu (1998) proposed a methodology for the analysis of finite buffer cellular manufacturing systems with unreliable machines. An open stochastic queuing network was used to model the system, and to develop an approach for designing the appropriate buffer size and to evaluate the throughput time of a cellular manufacturing system. But according to lean manufacturing principles where the objective is to do more with less, redundancy is not a feasible solution.

All afore mentioned literature provided some of the ways to handle machine failure in a cellular layout but none of them proposed ways to improve the reliability of machines/ manufacturing cells. Machine tool is the most critical component of a manufacturing cell and improving the reliabilities of machine tools improves the manufacturing cells reliability.

The number of papers dealing with the reliability of machine tools is very limited due to the proprietary nature of data. Wang et al (1998) proposed a failure probabilistic model for CNC lathes. Their analysis included field failure data collected over a period of two years on approximately 80 CNC lathes in China. The data were fit to a probability distribution using the rating matrix approach. The results of the above study showed that the lognormal and Weibull were the most appropriate for describing time between failure data. The lognormal provided the best fit to describe the repair times of the CNC lathes. Also it was identified that the electrical and electronic components contributed the most towards failure of CNC lathes.

Yazhou et al (1993) conducted a research very similar to the one mentioned above. Field failure data of 24 Chinese CNC machine tools were studied over a period of one year. The failure data were fit to both Weibull and exponential in order to determine the best fit to represent the underlying failure distribution. The data were also fitted on a Weibull paper. The fitted plots were evaluated for goodness-of-fit by correlation analysis. The analysis of the linear correlation has been found to be more significant for the exponential distribution. From the findings of data analysis, the study concluded that the failure pattern of machining centers fits exponential distribution and one can estimate reliability based on this finding.

Gupta and Somers (1989) developed multiple input transfer function modeling to explore the relationships between the downtimes, type of breakdown, and uptimes of CNC machines. Their model provided a method to analyze interrelated sources of data. Their results showed that uptime is not a leading indicator of downtime. They claimed that their transfer function model can be used in plants to schedule preventive maintenance and forecast CNC machine downtimes.

Liu et al (2010) analyzed the field failure data from 14 horizontal machining centers (HMC) over one year collected from an engine machining plant in China. They used generalized linear mixed model for analyzing the field failure data from the HMCs. They also used modified Anderson-Darling goodness of fit test to validate their results. They suggested that generalized linear mixed model is effective to analyze reliability of HMC.

Keller and Kamath (1987) conducted a reliability and maintainability study of computer numerical control machine tool through the analysis of field failure data collected over a period of three years on approximately 35 CNC machine tools during their warranty period. In order to apply quantitative reliability methods they developed a coding system to code failure data which were then collated into a data bank. Their results indicate that the lognormal and Weibull distributions were applicable to describe time between failures and the repair times, respectively. They used Duane reliability growth model to fit the reliability growth for the CNC system. They concluded their study claiming that the CNC machine tool is available only 82-85% of the time.

Dai et al (2003) applied a type I censor likelihood function to make the fitting of Weibull distribution of time between failures of machining center. They also used Hollander's goodness of fit tests to prove that the time between MC failures follows a Weibull distribution. But they failed to clearly clarify the type of machining center analyzed and also failed to mention whether the failure data corresponded to a single failure mode or mixed failures.

Analyzing the failure distributions of each machine in the manufacturing cells/transfer lines and estimating the corresponding reliability based on it can be useful in improving the machines reliability. This can be achieved by selecting a suitable maintenance technique based on the reliability function and the failure distribution of the manufacturing cell. The above mentioned methodology is the one that is to be used in this thesis where the objective is to find the appropriate failure distribution and maintenance methods to analyze and improve the reliability of machine tools and thereby improving the reliability of manufacturing cells.

CHAPTER 3

Manufacturing cells and Transfer Lines – An Overview

A manufacturing system is a set of machines, material handling equipment, computers, storage buffers, people and other items that are used together for manufacturing. These items are often termed as resources. Rephrasing Cochran's (2002) statement, manufacturing systems can be considered as a physical solution to a functional requirement. Each manufacturing system is unique in nature satisfying or trying to satisfy its own functional requirement. The reliability/availability of two completely different types of manufacturing systems is compared in this thesis: a manned manufacturing cell and an automated unmanned transfer line. They differ from one another in their system design, purpose, economics and both of them have their own advantages (and disadvantages). Both of the above mentioned systems are still being widely used especially in the automotive manufacturing sector.

3.1 Manufacturing Cells:

The concepts of manufacturing cells was perceived in the mid 1920's but was pioneered by Toyota in the 1980's. Flanders (1925) described the use of product-oriented departments to manufacture standardized products with minimal transportation. Bulbridge (1960) proposed a concept of grouping un-similar machines together to produce a family of parts. The parts or components were grouped together based on similarity of their manufacturing processes to form a part family, and machines were grouped together to form manufacturing cells to machine part families. In other words machines are dedicated to manufacture a family of parts. This method was termed Group technology and is one basis for forming manufacturing cells. The concept of (re)organizing the factory to form manufacturing cells and assembly cells is called cellular manufacturing.

A manufacturing system satisfies or tries to satisfy its functional requirements. Toyota implemented manufacturing cells with the functional requirement of one piece flow which reduces in-process inventory, identifies defects at the source, reducing setup time, minimizes labor and improves flexibility. Many companies have tried to imitate Toyota's manufacturing system and their manufacturing cell design to achieve the above mentioned functional requirements that Toyota achieved

The Toyota Motor Company designed a new manufacturing system with the goal of eliminating waste from their manufacturing processes. They named their new manufacturing system design as Toyota production system (TPS) which is now mostly referred to as the Lean production system. Taiichi Ohno at Toyota redesigned the machine shop into U-shaped manufacturing cells in the late 1940's (Black). The manufacturing cells were built with machine tools modified to be simple single cycle automatic machine tools with quick change tooling and poka-yoke devices (Defect prevention device built in them for defect prevention). Ultimately, one of the goals of the lean manufacturing cells is to eliminate all non-value added movements; and hence it's U-shape. The U-shape puts the first and the last process close to one another. When a worker has finished a process, s/he simply turns around and is back to step one. The use of machines in a designated physical area for production of a specific group of parts facilitates production planning, scheduling, control substantially and reduces the setup time (hence batch sizes), material handling, WIP and throughput time.

Toyota designed a manufacturing system to eliminate waste. Taiichi Ohno identified 7 deadly wastes in a manufacturing/production system as defects, overproduction, waiting, excessive transportation, inventory, excessive motion and extra Processing. The eighth waste of not utilizing people was later added to the 7 deadly manufacturing wastes. In general, if an action does not directly add value to the product being produced, the action is wasteful. Toyota developed various tools and techniques to eliminate sources of the above mentioned wastes. Table 3.1 summarizes the Lean tools and the resulting minimum waste. A brief description of manufacturing wastes and lean tools is provided in Appendix

Table 3.1: Lean Tools and Manufacturing waste:

Waste Eliminated / Lean Tool	Defects	Over Production	Waiting	Not utilizing people	Excessive Transportation	Inventory	Excessive Motion	Extra Processing
Manufacturing cells- Standard work	×		×	×	×	×	×	
Pull System/Kanban		×				×		
Poka-yokes	×							×
Quick Changeover			×	×				×
Batch Reduction		×	×			×		
Point Of Use Storage					×		×	
Value Stream Mapping			×		×		×	×
5S			×		×		×	
Total Preventive Maintenance	×		×					×
Mixed Model Final Assembly			×					×

From the above table it can be seen that manufacturing cells are helpful in decreasing the source of some of the above mentioned manufacturing wastes. In addition, manufacturing cells can lead to higher operator utilization. Black (2003) states in a Lean enterprise the operators in the manufacturing cells are multi-functional and multi-process, i.e., they can operate all machine tools in the manufacturing cell and they can perform a variety of value added activities such as problem solving, setup reduction, routine preventive maintenance, continuous improvement and so on.

A manufacturing cell consists of a set of machine tools placed close to each other in series. Some of the Machine tools in manufacturing cells are precise CNC machines. In some cases, a manufacturing cell may even contain a small transfer line. The manufacturing cell is U-shaped so that the first and the last process in the cell can be placed close to each other. Thus the operator has a better control of the stock-on-hand in the cell. Black (2003) provides rules for designing/implementing manufacturing cells – all the machine tools in the manufacturing cell has machining/processing time less than the necessary cell cycle time and all the machine tools in the manufacturing cell are simple yet precise single cycle automatic machine tools. Single cycle automatics are an example of JIDOKA – separating machine's task from operator's task.

The manufacturing cell considered in this thesis has four CNC machine tools – Lathe, Drilling/Boring machine, Milling machine and a center-less Grinding machine. It is a manned manufacturing cell. The manufacturing cell machines a family of crankshafts and connecting rods for lawnmower engines.

3.2 Transfer Lines:

A Transfer Line is a manufacturing system with a linear network of service stations or machines. The work piece gets machined at every station of a transfer line and the transportation (the transfer) between stations is automatic, which is accomplished through conveyer lines connecting the stations. Because the work sequence of the part is fixed, automated material handling systems are often found as link between stations. A raw work piece enters on one end of the line, and manufacturing process is performed sequentially as the part progresses forward. The line may include inspection stations for quality checks. Transfer lines have very high production rates. Multiple parts are processed simultaneously, one part at each workstation. In steady state the number of parts in the transfer line is equal to the number of stations in the transfer line (Assuming no buffers are allocated in between stations). Each station performs different tasks, so that all operations are required to complete one unit of work. Because all parts flow through the same set of stations, the cycle times at each station must be about the same duration. The capacity of the entire line will be determined by the longest cycle time. In other words, the workstation with the longest cycle time sets the pace of that line. When a transfer line has a fixture design specific to the geometry of work piece being machined, it is called a *palletized* transfer line.

Transfer line is a very complex manufacturing system comprising of mechanical, electrical, electronic, hydraulic / pneumatic and computer components. A transfer line has approximately 100,000 critical components which are essential for its operation. Due to its structure the reliability of a transfer line cannot be greater than the reliability of its most unreliable station. The complexity of the transfer line increases with the addition of stations. Also the reliability of the transfer lines decreases with the addition of stations.

Groover (2001) mentions transfer lines are applicable only under the following conditions:

- High product demand requiring high product quantities
- Stable product design – Frequent design changes are difficult to cope with on an automated production line
- Long product life, at least several years in most cases
- Multiple operations are performed on the product during its manufacture

In other words, transfer lines represent physical solutions to the above mentioned functional requirements. Transfer lines have the advantage of having high production rates, reduced labor requirements and floor space, etc.

Transfer lines represent highly automated manufacturing systems and are very common in machining engine block castings, cylinder heads, crankshafts, etc. They are used in high volume manufacturing/mass production environment. Transfer lines require a significant capital investment, their capital costs range from $200,000 to $30,000,000. Since transfer lines are capital intensive, they must be kept running to be economically justifiable.

The transfer line considered in this thesis is a 15-station automated transfer line which performs a variety of drilling, boring, milling, honing operations for machining engine block castings, cylinder heads and connecting rods. This transfer line has a production capacity of 1500 to 2000 units per 8 hour shift or about 0.25 minutes/part.

CHAPTER 4

Reliability in Manufacturing Systems Design

Manufacturing systems design (MSD) is a methodology of assembling machines, materials, labor, material handling devices, computers, etc. to produce goods according to customer/design requirements. Every manufacturing system is designed to deliver profit to the organization. Mathematically, Profit ≈ Revenue – Cost. So to increase profit, sales must be increased and/or the cost of making the goods has to be minimized. Manufacturing systems should be designed to reduce costs. Manufacturing strategies that increases sales are quality of the product, reliability of the product, product design, price reduction, etc. Some of the manufacturing strategies to reduce manufacturing costs are WIP reduction, setup time reduction, labor reduction, defect prevention (eliminates rework), etc.

The Ford motor company designed the first mass production system to reduce the manufacturing cost through economy of scale. Toyota designed the first lean production system to eliminate waste and reduce inventory thereby reducing the cost of manufacturing. Manufacturing systems should be designed to decrease the operating cost by reduction and/or increasing sales through better product quality & reliability.

Unreliable machines increase manufacturing costs. Unreliable machines can sometimes halt entire production causing delays in the production and might also lead to scheduling problems. In other words, unreliable machines increase manufacturing cost and thereby reduce profit. Unreliable machines can also sometimes lead to unreliable products which create quality issues which increases the warranty claims, recalls and reduces reputation of the organization which affect the sales of the organization. Unreliable machines also increases the manufacturing lead time which often leads to increases in buffer inventories.

The effect of unreliable machines on the manufacturing system's performance is dependent on its design. The severity of unreliable machines in cellular manufacturing and serial production lines/transfer lines is greater than in a functional job shop. In a job shop, the machines are grouped together by machine type (such as the lathe department, drilling department, etc.). In case of a machine failure it can be easily rerouted to an available machine in that department. In case of serial production lines/cellular layout, the unavailability of any one of the machines/stations can lead to stoppage of the entire system. In cellular manufacturing, the machines are grouped together and dedicated to machine a family of parts and failure of any one machine tool will halt the entire production of the manufacturing cell.

Reliability should be a consideration in manufacturing systems design. But design for reliability is an iterative process and should be improved on a continuous basis. To effectively improve reliability, the life time of the critical components in the machines should be obtained. Once the lifetime of the critical components is obtained, periodic replacement of those components can prevent unplanned downtime of the machines. There are two approaches in lifetime testing – empirical methods and reliability testing. In empirical methods, field failure data is collected and fitted to statistical distributions. Reliability estimates are derived from parameters of the statistical distribution. In reliability testing, the components are tested in an experimental setting in attempt to generate failures in order to identify failure modes and eliminate them.

Reliability testing is not feasible for machine tools and production lines since the number of components involved is very high. But reliability of machines could be improved by collecting failure data and assessing reliability form the collected data. Once the failure data is obtained, it can be fitted to a statistical distribution and the lifetime of components/systems can be estimated. Collecting failure times and the reason for failures are necessary to improving the reliability of manufacturing system.

Once reliability measures such as reliability function, mean time between failures and failure rates are estimated, necessary maintenance and replacement techniques could be formulated to improve manufacturing uptime.

CHAPTER 5

Reliability/Availability assessment of Manufacturing Cell

To assess and compare the reliability of manufacturing/machining cell versus a Transfer line, failure data were collected from a manufacturing cell as well as a transfer line from a manufacturing plant that produces small engines for lawn mowers. The manufacturing facility machines the engine block castings and cylinder heads castings on its 15 station completely palletized transfer line and the crankshafts that go into the engines are manufactured at the manufacturing cell. The failure data correspond to the past three years of operations.

Manufacturing/Machining Cell:

The manufacturing/machining cell consists of four CNC machine tools, i.e., a lathe, milling machine, drilling/boring machine and a Grinding machine.

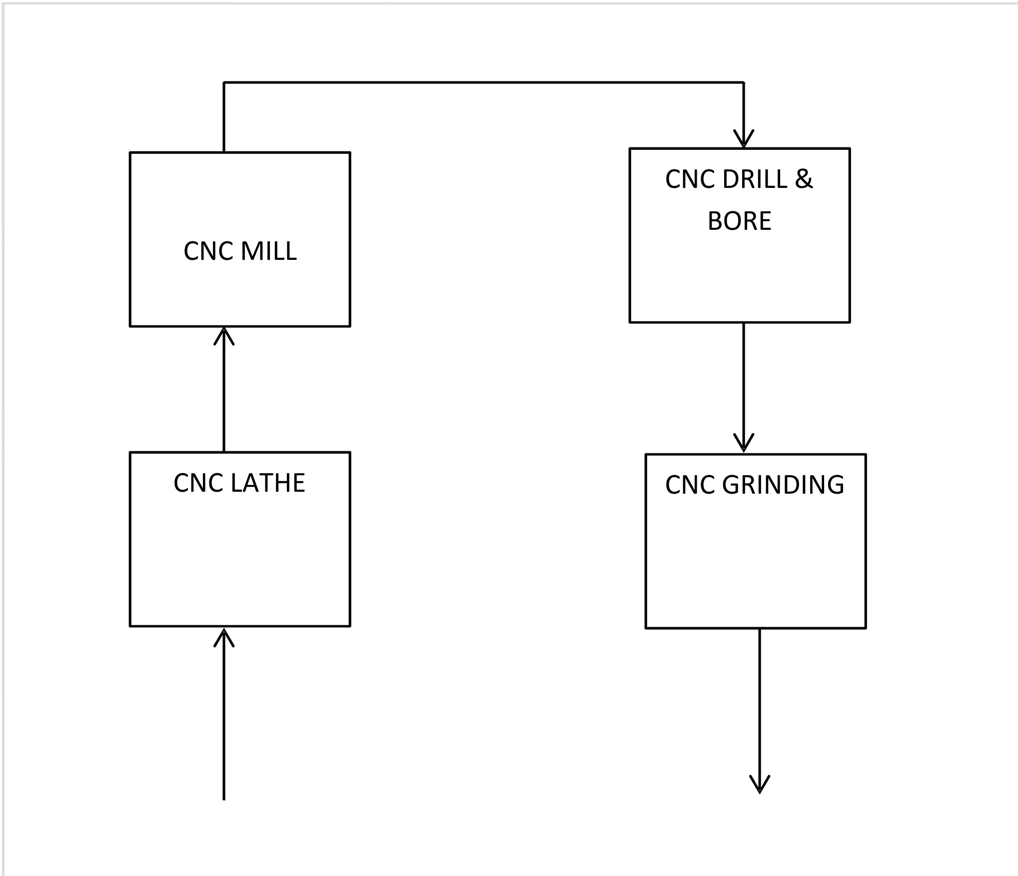

Figure 5.1: Crankshaft manufacturing cell

The machining of the crankshaft is done in a sequential one piece flow in the manufacturing cell. The work piece is first machined on the lathe and then it is moved on to the milling machine and then to the drilling machine and finally on to the grinding machine. All the machine tools are necessary to complete the machining of the crankshaft.

From a reliability standpoint the above manufacturing cell can be considered as a system comprising of machine tools placed in a serial configuration as the critical components. So the system reliability is dependent on the reliability of the individual machine tools. Mathematically the reliability of the manufacturing cell is the product of the reliability of the individual machine tools. This implies that the reliability of the manufacturing cell can be no greater than that of the most unreliable machine tool in the manufacturing cell.

Generally there are two approaches in fitting reliability distributions to failure data. The first method is to fit a theoretical distribution. The second approach is to empirically derive the reliability function and/or hazard function directly from the reliability data. The first approach is better suited for the above problem as it presents the advantage of estimating the manufacturing cell mean time between failures (MTBF) from the derived distributions.

The reliability of the manufacturing cell can be obtained from fitting the failure data into a theoretical distribution. From the time between failures of individual machine tools, the failure distribution of the individual machine tools can be obtained using goodness of fit tests. Then the reliability measures for each of the individual machine tools can be obtained from their specific failure distribution. After obtaining the reliability measures of the individual machine tools the manufacturing cell reliability can be computed as the product of the reliability of the individual machine tools.

Time between failure data from the manufacturing cell:

The time between failures of the individual machine tools and the reasons for failure for the period of 3 years is given in Tables 5.1, 5.2, 5.3 and 5.4 below. The failure times are field/operational failure times that were recorded as and when the failures occur and the failure times are not censored. Also the failures of the machine tools are independent of each other.

The repair times were not usually recorded for the machine tool because whenever there is a failure in the machine tool it is mostly not repairable such as electric motor burnt out, cutting tool breakage, rheostat/fuse burn out, etc. So the part is usually replaced. If the time to repair times are negligible when compared to the time between failures the reliability is the estimate of the availability. Mathematically,

Availability = Uptime/ (Uptime +Downtime)

So when repair times are negligible Availability ≈ Reliability

Even though the repair time is negligible, it does represent some downtime. Unfortunately the manufacturing facility does not record the repair time of their machine tools in their manufacturing cell. This is because most of the time when failure occurs it results in replacement not repair. But the operators and the maintenance engineer based on their experience denote that the downtime/replacement time for their individual machine tools on an average is 1 hour.

Table 5.1: Time between failures of CNC lathe: (Source: Briggs and Stratton)

Time between failures, hours	**Reason For Failure**
643	Spindle motor Failure
207	Electrical Relay failure
567	Cutting tool broken
252	Electric motor Damage
212	Fuse Burnt
216	Rheostat Failure
251	Coolant line clogged
190	Software Failure
354	Spindle motor Failure
109	Limit switch damaged
390	Pneumatic chuck failed to open
816	Stepper motor failure
500	Coolant pump failure
50	Transmission Failure
375	Turret Failure
553	Control Panel not Responding
303	Lubricant system failure
700	Fuse Burnt
351	Spindle Failure
187	Servo Motor Failure
157	Control Panel not Responding
284	Cutting tool broken
207	Pneumatic chuck failed to open
660	Internal Gear Failure
476	Electric motor Damage
652	Transmission Failure
658	Rheostat Failure
197	Coolant line clogged
107	Lubricant system failure
389	Stepper motor failure
86	Swarf Mechanism Failure

Table 5.2: Time between failures for CNC Milling machine: (Source: Briggs and Stratton)

Time between failures, hours	**Reason for Failure**
520	Electrical Relay Failure
205	Coolant pump Failure
407	Spindle motor failure
813	Coolant line clogged
467	Lubricant system failure
321	Electric motor damage
1626	Software failure
598	Electric motor damage
2	Cutting tool broken
640	Stepper motor failure
412	Fuse burnt
18	Coolant line clogged
539	Rheostat Failure
174	Transmission failure
357	Cutting tool broken
36	Servo motor failure
98	Spindle motor failure

Table 5.3: Time between failures for CNC Drilling/Boring machine: (Source: Briggs and Stratton)

Time between failures, hours	Reason for Failure
827	Cutting tool broken
464	Spindle motor Failure
568	Electric motor Damage
503	Automatic Tool change failure
558	Electrical Relay failure
104	Coolant pump failure
254	Electrical Relay failure
187	Control Panel not Responding
884	Stepper motor failure
456	Fuse Burnt
64	Pneumatic chuck failed to open
113	Transmission Failure
302	Cutting tool broken
739	Spindle motor Failure
313	Electric motor Damage
342	Lubricant system failure
229	Automatic Tool change failure
733	Electric motor Damage
89	Stepper motor failure
210	Electrical Relay failure
293	Cutting tool broken
156	Automatic Tool change failure
581	Coolant line clogged
779	Electrical Relay failure
305	Stepper motor failure
23	Electric motor Damage
412	Rheostat Failure
376	Spindle motor Failure
472	Cutting tool broken
493	Fuse Burnt
676	Control Panel not Responding
153	Pneumatic chuck failed to open
436	Transmission Failure
715	Turret Failure

Table 5.4: Time between failures of CNC Grinding machine (Source: Briggs and Stratton)

Time between failures, hours	Reason for Failure
1065	Grinding wheel wear
868	Software failure
785	Electrical relay failure
742	Grinding wheel wear
572	Fuse burnt
72	Electrical motor damage
448	Rheostat failure
831	Spindle motor failure
223	Transmission failure
485	Grinding wheel wear
454	Stepper motor damage
144	Electrical relay failure
93	Servo motor failure
756	Grinding wheel wear
689	Pneumatic chuck fail to open
816	Spindle motor failure

The above failure data for the individual machine tool can be fit into a relevant theoretical distribution using goodness of fit tests. But before using the goodness of fit tests it should be noted that the above failures are caused by different failure modes. Usually in Reliability engineering when estimating product reliability it is not a recommended practice to mix the failure times from various failure modes. But the following analysis is for estimating process reliability (which is the availability) rather than product reliability. In other words the focus here is on how long/how often the machine is unavailable so that it affects the production rather than by what mode it failed. Also the lack of availability of sufficient data for each failure modes makes it impractical to estimate the reliability measures for each failure modes. The above task could be better accomplished by reliability testing on machine tools rather than collecting field failure data.

5.1 Identifying appropriate TBF distribution for individual machine tools in crankshaft manufacturing cell:

5.1.1 CNC Lathe:

Form the recorded failure data of CNC lathe the Goodness of fit tests were conducted on Minitab© statistical software. Minitab uses Anderson – Darling statistic test to measure how well the data follows a particular distribution. The better the distribution fits the data, the smaller this statistic will be. The results of the tests for the failure data from the CNC lathe are given below

Table 5.5: Minitab Goodness of test results for CNC Lathe TBF:

Distribution	**Anderson-Darling Statistic**	**P value**
Normal	0.811	0.032
Box-Cox Transformation	0.401	0.34
Lognormal	0.413	0.318
3-Parameter Lognormal	0.39	*
Exponential	2.308	0.004
2-Parameter Exponential	1.617	0.013
Weibull	**0.406**	**>0.250**
3-Parameter Weibull	0.351	0.482
Smallest Extreme Value	1.254	<0.010
Largest Extreme Value	0.48	0.228
Gamma	**0.357**	**>0.250**
3-Parameter Gamma	0.345	*
Logistic	0.801	0.021
Loglogistic	**0.407**	**>0.250**
3-Parameter Loglogistic	0.404	*

From the Goodness of fit test results from Minitab© the Gamma Distribution and the Weibull distribution provide the best fit for representing the failure distribution of the CNC lathe in the manufacturing cell. Between these two distributions using the Weibull has more advantages than the gamma distribution because the Weibull shape parameter β gives a good description of type of failure (See table below).

Weibull Shape parameter (β)	Representation of
β<1	Infant mortality (Decreasing failure rate)
β=1	Constant failure rate
β>1	Increasing failure rate, Wear out failures

Before estimating the Weibull parameters a Weibull goodness of fit test must be conducted to make sure that the failure times is Weibull distributed, also Minitab© only gives approximate P values for the Weibull fit (>0.250) and the Weibull goodness of fit is required to obtain the exact P value to justify the use of the Weibull distribution to represent the failure times of the CNC lathes.

Mann's Test for the Weibull Distribution:

A goodness of fit test for the Weibull distribution is a test developed by Mann, Schafer and Singpurwalla [1974]. The hypotheses are

H_0: The failure times are Weibull

H_1: The failure times are not Weibull

The test statistic is

$$M = \frac{k_1 \sum_{i=k_1+1}^{r-1} [(\ln t_{i+1} - \ln t_i)/M_i]}{k_2 \sum_{i=1}^{k1} [(\ln t_{i+1} - \ln t_i)/M_i]}$$

Where $k_1 = \left\lfloor \frac{r}{2} \right\rfloor \qquad k_2 = \left\lfloor \frac{r-1}{2} \right\rfloor$

$M_i = Z_{i+1} - Z_i$

$$Z_i = \ln[-\ln(1 - \frac{i - 0.5}{n + 0.25})]$$

r = n = number of failures and $\lfloor x \rfloor$ is the integer portion of x. If $M > F_{\alpha,2k_2,2k_1}$,then the null hypothesis is rejected. Values of F_α can be obtained from tables of F-distribution for a specified critical value α where the numerator degrees of freedom is $2k_2$ and denominator degrees of freedom is $2k_1$.

For the failure times of the CNC lathe the value of n = r = 31 and $k_1 = k_2 = 15$.

The M statistic calculated from the above formula is M = 1.264983

The critical value is $F_{0.05, 30, 30}$ is $F_{0.05, 30, 30} = 1.840872$, which shows that $M < F_{0.05, 30, 30}$. So the decision is to fail to reject the null hypothesis and conclude that the failure times are Weibull distributed with 95% confidence. The *P value* from the above test is 0.60 which is sufficiently large to support the decision of failing to reject H_0 at the 5% level.

The Weibull Distribution:

The 2-parameter Weibull distribution is a continuous distribution that may be used to represent increasing/decreasing/constant failure rates. It is characterized by parameters β and θ, where β is the shape parameter for Weibull distribution and θ is the characteristic life of the Weibull distribution.

Estimating the Weibull parameters β and θ using Maximum likelihood estimation (MLE):

The probability density function (pdf), f (t) of the 2-parameter Weibull distribution is given by

$$f(t) = \frac{\beta}{\theta^{\beta}} t^{\beta-1} e^{-(t/\theta)^{\beta}}$$

This implies that the probability element of the i[th] failure time, t_i, is given by

$\frac{\beta}{\theta^{\beta}} t_i^{\beta-1} e^{-(t_i/\theta)^{\beta}}$ dt_i and hence the LF (likelihood function) is given by

$$L(\theta, \beta) = \prod_{i=1}^{n} \frac{\beta}{\theta^{\beta}} t_i^{\beta-1} e^{-(t_i/\theta)^{\beta}} = \left(\frac{\beta}{\theta^{\beta}}\right)^{n} \times \left[\prod_{i=1}^{n} t_i^{\beta-1}\right] \times e^{-\sum_{i=1}^{n}(t_i/\theta)^{\beta}} \qquad (1)$$

Taking the natural log of (1) leads to

$$\text{Ln } L(\theta,\beta) = n[\ln(\beta) - \beta \ln(\theta)] + (\beta - 1)\sum_{i=1}^{n} \ln(t_i) - \sum_{i=1}^{n}(t_i/\theta)^{\beta} \qquad (2)$$

The partial derivative of the Log-likelihood, $\ln(\theta, \beta)$, wrt θ is given by

$$\partial[\text{Ln } L(\theta, \beta)]/\partial\theta = -n\beta/\theta - \frac{\partial}{\partial\theta}\left[\theta^{-\beta}\sum_{i=1}^{n}(t_i)^{\beta}\right] = -n\beta/\theta + \beta\,\theta^{-\beta-1}\sum_{i=1}^{n}(t_i)^{\beta} \xrightarrow{\text{Set to}} 0 \qquad (3)$$

The solution to equation (3) is the MLE of θ which is given below.

$$\hat{\theta} = \left[\frac{1}{n}\sum_{i=1}^{n} t_i^{\hat{\beta}}\right]^{1/\hat{\beta}} \qquad (4)$$

Equation (4) is the result that is needed to obtain the point MLE of the characteristic life θ, but the difficulty lies in the fact that unless the point MLE of the slope β is known the value $\hat{\theta}$ cannot be computed from Eq. (4). So the MLE of β has to obtained first by partially differentiating $\ln(\theta,\beta)$ with respect to β.

$\xi(\beta) = \partial\ln(\theta, \beta)/\partial\beta = \frac{n}{\beta} - n\ln(\theta) + \sum_{i=1}^{n}\ln(t_i) - \left[\sum_{i=1}^{n}\frac{\partial}{\partial\beta}(t_i/\theta)^{\beta}\right]$; bearing in mind that

$\frac{\partial}{\partial\beta}(t_i/\theta)^{\beta} = \frac{\partial}{\partial\beta}e^{\ln(t_i/\theta)^{\beta}} = \frac{\partial}{\partial\beta}e^{\beta\ln(t_i/\theta)}$ then it follows that

$$\partial[\text{Ln } L(\theta, \beta)]/\partial\beta = \frac{n}{\beta} - n\ln(\theta) + \sum_{i=1}^{n}\ln(t_i) - \sum_{i=1}^{n}\left[(t_i/\theta)^{\beta} \times \ln(t_i/\theta)\right] \xrightarrow{\text{Set to}} 0 \qquad (5)$$

Equations (4) & (5) will have to be solved simultaneously in order to obtain the Maximum likelihood estimates of θ and β. Unfortunately, no closed-form exists for $\hat{\theta}$ and $\hat{\beta}$. Therefore, the solutions have to be obtained through trial and error that will make both partial derivatives $\partial \ln(\theta, \beta)/\partial\theta$ in (3) and $\partial \ln(\theta, \beta)/\partial\beta$ in (5) almost equal to zero. The above task can be accomplished through the Newton-Raphson algorithm.

Estimating the Weibull parameters for CNC Lathe:

Using the above mentioned maximum likelihood estimation procedure the Weibull parameter estimates for CNC lathe can be estimated using the time between failure data of the CNC lathe provided in Table 1. The parameter estimates is obtained using the following steps

(1) Arrange the time between failures data t_i's from smallest to largest, i.e. order the statistic, where the first order statistic represents the smallest time between failure data, the second order statistic the next smallest failure time and so on.

(2) Select an arbitrary value for β. A logical selection would be β greater than 1 because the CNC lathe is experiencing wear out failures as suggested from the data in Table 1. Elsayed (1996) also provides a good starting approximation of β which is given by $\hat{\beta}$ = 1.05/CV, where CV is the sample coefficient of variation from the failure data.

(3) Obtain the value of $\hat{\theta}$ using equation (4) and the arbitrary value of β. substitute the values of θ and β in equation (5)

(4) Continuously solve for different values of β and θ that makes the equation (5) almost zero to obtain the exact estimates of β and θ for the given Weibull data. This can be solved Newton-Raphson algorithm using an appropriate software program.

The estimates of β and θ for the time between failures of the CNC lathe were obtained using the above mentioned steps. The Newton-Raphson method was solved using Microsoft Excel© Equation solver. The results are summarized below

Machine tool	Time between failures distribution	Estimates of the distribution Parameters
CNC Lathe	Weibull	$\beta = 1.809278; \theta = 403.8257$

5.1.2 CNC Mill:

Form the recorded failure data of CNC mill the Goodness of fit tests were conducted on Minitab© statistical software. The results of the tests for the failure data from the CNC mill are given below

Table 5.6: Minitab Goodness of test results for CNC Milling machine TBF:

Distribution	**Anderson-Darling Statistic**	**P Value**
Normal	0.744	0.042
Box-Cox Transformation	0.304	0.534
Lognormal	1.215	<0.005
3-Parameter Lognormal	0.374	*
Exponential	**0.556**	**0.403**
2-Parameter Exponential	0.653	0.195
Weibull	0.562	0.144
3-Parameter Weibull	0.31	>0.500
Smallest Extreme Value	1.751	<0.010
Largest Extreme Value	0.295	>0.250
Gamma	0.57	0.117
3-Parameter Gamma	0.298	*
Logistic	0.357	>0.250

From the Goodness of fit test results from Minitab© the Exponential distribution provide good fit for representing the failure distribution of the CNC Mill in the manufacturing cell. The P-value of 0.403 is sufficiently large enough to support the decision of selecting the exponential distribution to represent the time between failures distribution of the CNC Milling machine. In addition the coefficient of variation (*CV*) of the time between failures data of the CNC milling machine is 0.9146 which is close to 1. So keeping in mind that exponential distribution has theoretical coefficient of variation of 1, the *CV* value of 0.9146 is sufficiently close to 1 to support the fact that the time between failure data for CNC milling machine is approximately exponentially distributed.

The Exponential Distribution:

The exponential distribution is a continuous distribution that is used to represent the constant failure rates. It is characterized by the parameter λ which represents the failure rate of the component (or system). The failure rate λ of the exponential distribution is constant with respect to time; this property of the exponential distribution is called the "memorylessness" property, i.e. is the time to failure of the component is independent of how long it has been operating. The exponential is the only continuous distribution in the universe with the memorylessness property. The exponential distribution is characterized only by its failure rate parameter λ, so if the parameter λ can be estimated, all the other reliability measures can be obtained from λ.

Estimating the Exponential parameter (λ) using Maximum likelihood estimation (MLE) :

The probability density function of an exponential random variable (pdf), f (t) is given by

$$f(t) = \lambda e^{-\lambda t} \qquad (6)$$

This implies that the probability element of the i^{th} failure time, t_i, is given by $\lambda e^{-\lambda t_i}$ dt_i and hence the likelihood function is given by

$$L(\lambda) = \prod_{i=1}^{n} \lambda e^{-\lambda t_i}$$

$$L(\lambda) = \lambda^n e^{-\lambda \sum_{i=1}^{n} t_i}$$

Taking natural logarithm on both sides

$$\ln[L(\lambda)] = \ln[\lambda^n e^{-\lambda \sum_{i=1}^{n} t_i}]$$

$$\ln[L(\lambda)] = n \ln(\lambda) - \lambda \sum_{i=1}^{n} t_i$$

Taking derivative with respect to λ

$$\frac{\partial}{\partial \lambda}[\ln(L(\lambda))] = \frac{n}{\lambda} - \sum_{i=1}^{n} t_i \xrightarrow{\textbf{Set to}} 0$$

$$\frac{n}{\hat{\lambda}} = \sum_{i=1}^{n} t_i$$

$$\hat{\lambda} = \frac{n}{\sum_{i=1}^{n} t_i} \qquad (7)$$

Equation (7) is the maximum likelihood estimate for the exponential distribution with failure rate λ. So the failure rate λ for the CNC milling machine can be found out using the time between failures data's from Table 2. From the time between failures data from table 2 and using equation (7) the failure rate λ for the CNC milling machine is estimated as

Machine tool	Time between failures distribution	Estimates of the distribution Parameters
CNC Mill	Exponential	λ=0.030323 per hour

5.1.3 CNC Drilling and Boring machine:

Form the recorded failure data of CNC drilling and boring machine the Goodness of fit tests were conducted on Minitab© statistical software. The results of the tests for the failure data from the CNC drilling and boring machine are given below

Table 5.7: Minitab Goodness of test results for CNC Drilling & Boring machine TBF:

Distribution	Anderson-Darling Statistic	P Value
Normal	0.345	0.464
Box-Cox Transformation	0.234	0.778
Lognormal	0.883	0.021
3-Parameter Lognormal	0.277	*
Exponential	2.082	0.007
2-Parameter Exponential	2.095	<0.010
Weibull	**0.265**	**>0.250**
3-Parameter Weibull	0.243	>0.500
Smallest Extreme Value	0.773	0.041
Largest Extreme Value	**0.297**	**>0.250**
Gamma	**0.393**	**>0.250**
3-Parameter Gamma	0.28	*
Logistic	**0.379**	**>0.250**
Loglogistic	0.634	0.061
3-Parameter Loglogistic	0.319	*

From the above results the Weibull distribution is the most appropriate for fitting the failure times. The *P-value* of more than 0.250 is sufficient enough to support the selection of the Weibull distribution to represent the failure time distribution for the CNC drilling/boring machine. The exact *P-value* using the Mann's goodness of fit test for Weibull distribution developed before is 0.905. Using the same procedure as developed for CNC lathe for estimating the Weibull parameters the Weibull parameter estimates for the CNC drilling/boring machine is given below

Machine tool	Time between failures distribution	Estimates of the distribution Parameters
CNC Drill/Bore	Weibull	$\beta = 1.718139$; $\theta = 453.7725$

5.1.4 CNC Grinding machine:

Form the recorded failure data of CNC grinding machine the Goodness of fit tests were conducted on Minitab© statistical software. The results of the tests for the failure data from the CNC grinding machine are given below

Table 5.8: Minitab Goodness of test results for CNC Grinding machine TBF:

Distribution	**Anderson-Darling Statistic**	**P Value**
Normal	0.459	0.228
Box-Cox Transformation	0.459	0.228
Lognormal	1.213	<0.005
3-Parameter Lognormal	0.5	*
Exponential	1.525	0.026
2-Parameter Exponential	1.501	0.011
Weibull	0.846	0.024
3-Parameter Weibull	0.406	0.259
Smallest Extreme Value	**0.324**	**>0.250**
Largest Extreme Value	0.718	0.051
Gamma	0.954	0.02
3-Parameter Gamma	0.765	*
Logistic	0.476	0.188

Loglogistic	1.077	<0.005
3-Parameter Loglogistic	0.479	*

From the above results the smallest extreme value distribution is the only distribution that is appropriate for fitting the failure times for the CNC grinding machine.

The smallest extreme value distribution:

The smallest extreme value distribution is closely related to the Weibull distribution in that if the time between failures (TBF) has a Weibull distribution, then log(TBF) has an extreme value distribution. Lawless (2003) states that an extreme value distribution is an asymptotic distribution resulting from finding the minimum or maximum of a large number of observations from an underlying unbounded population.

Estimating the Smallest extreme value parameters α and μ using Maximum likelihood estimation (MLE):

The probability density function (pdf), f(t) for the smallest extreme value distribution is given by

$$f(t) = (\frac{1}{\alpha})e^{\frac{(t_i-\mu)}{\alpha}} e^{-e^{\frac{(t_i-\mu)}{\alpha}}} , \qquad (8)$$

where α is the scale parameter and μ is the location parameter of the smallest extreme value distribution. The likelihood function L(α, μ) is given by

$$L(\alpha,\mu) = \prod_{i=1}^{n} (\frac{1}{\alpha})e^{(\frac{(t_i-\mu)}{\alpha})} e^{-e^{(\frac{(t_i-\mu)}{\alpha})}} \qquad (9)$$

Taking natural logarithm on both sides

$$\ln[L(\mu,\alpha)] = -n\ln\alpha + \sum_{i=1}^{n}\frac{(t_i-\mu)}{\alpha} - \sum_{i=1}^{n} e^{\frac{(t_i-\mu)}{\alpha}}$$

Maximum likelihood estimates can be found by taking the partial derivatives of the log likelihood function with respect to α and then μ and equating them to zero, i.e. by setting

$$\frac{\partial \ln L(\alpha,\mu)}{\partial\alpha} = \frac{\partial \ln L(\alpha,\mu)}{\partial\mu} = 0$$

and solving for α and μ. Following Lawless (2003), $\frac{\partial \ln L(\alpha,\mu)}{\partial\mu} = 0$ can be solved for μ

$$\mu = \alpha \ln[\frac{1}{r}\sum_{i=1}^{n} e^{\frac{t_i}{\alpha}}] \tag{10}$$

, substituting this into $\frac{\partial \ln L(\alpha,\mu)}{\partial\alpha}$ =0 results in:

$$-\alpha - \frac{1}{n}\sum_{i=1}^{n} t_i + \frac{\sum_{i=1}^{n} t_i e^{\frac{t_i}{\alpha}}}{\sum_{i=1}^{n} e^{\frac{t_i}{\alpha}}} = 0 \tag{11}$$

Equations (10) and (11) can be solved numerically for α and μ by the Newton-Raphson procedure mentioned previously with the help of Microsoft Excel© solver. The results are summarized below

Machine tool	Time between failures distribution	Estimates of the distribution Parameters
CNC Grinder	Smallest extreme value	α = 251.628; μ = 707.3796

Summary of distribution parameter(s) estimates for the machine tools in the manufacturing cell:

Thus far the appropriate distributions for the time between failures of the machine tools in the manufacturing cell has been determined by Goodness of fit tests for specific distributions and the parameter estimate(s) for the individual distributions have been determined by maximum likelihood estimation. Once the individual distribution and the distribution parameters for the time between failures of the machine tools are estimated all the reliability measures such as the reliability function, hazard rate function and the Mean time between failures (MTBF's) for the individual machine tools and hence the manufacturing cell reliability measures can be estimated. The summary of the results of the estimations thus far are given below

Table 5.9: Distribution parameter(s) estimates for the machine tools in the manufacturing cell:

Machine tool	Time between failures distribution	Estimates of the distribution Parameters
CNC Lathe	Weibull	$\beta = 1.809278$; $\theta = 403.8257$
CNC Mill	Exponential	$\lambda=0.00279$
CNC Drill/Bore	Weibull	$\beta = 1.718139$; $\theta = 453.7725$
CNC Grind	Smallest extreme value	$\alpha = 251.628$; $\mu = 707.3796$

5.2 Reliability measures for the machine tools in the manufacturing cell:

As mentioned previously, reliability is the probability that a component (or) equipment will perform a required function for a given period of time when used under stated operating conditions. The most commonly used reliability measures in manufacturing are point reliability function (reliability for a specified time period) and mean time between failures. Before assessing the point reliability of the individual machine tools, the term specified time period has to be decided. The manufacturing facility from which the failure data was collected has a scheduled monthly preventive maintenance, so a good time period would be one month (approximately 160 hours). For now it is assumed that the preventive maintenance increases the time between failures of the machines. In other words, for the case mentioned above, a machine tool is considered available if it does not breakdown or fail for 160 hours of its operation or if the time to failure exceeds 160 hours of operation. Mathematically it can be expressed as

$$R(t) = \Pr(T > t)$$

, where T is the time between failure (TBF), with Pr (Probability) density function f(t). So

$$R(t) = \Pr(T > t) = \int_t^{\infty} f(t)dt$$

The pdf (Pr density function), f(t) is also referred to as failure (or mortality) density function. The Reliability function R(t) can also be expressed in terms of the cumulative density function F(t), which is the cumulative failure probability by time t.

$$R(t) = \Pr(T > t) = \int_t^{\infty} f(t)dt = 1 - \Pr(T \le t) = 1 - F(t) \qquad (12)$$

The relationship between f(t) and R(t) can be obtained by differentiating equation (12) with respect to t. Using the fact that f(t) = dF(t)/dt, $F(t)=\int_{-\infty}^{t} f(t)dt$, since time can be never negative the lower limit of the integral should be replaced with zero which gives the result

$$F(t)=\int_{0}^{t} f(x)dx \tag{13}$$

Using equations (12) and (13)

$$\frac{dR(t)}{dt}=\frac{d}{dt}[1-F(t)]=-\frac{dF(t)}{dt}=-f(t)$$

, which implies that

$$f(t)=-\frac{dR(t)}{dt} \tag{14}$$

The relationship between the failure density function f(t) and the reliability function R(t), which is given by equation (14) is needed to derive the mean time between failures (MTBF), which is the expected value (E) of the random variable T.

$$MTBF=E(T)=\int_{0}^{\infty} tf(t)dt$$

$$MTBF=E(T)=\int_{0}^{\infty} t[-dR(t)] \quad \text{[Using (14)]}$$

Integration by parts yields

$$MTBF=\int_{0}^{\infty} R(t)dt \tag{15}$$

Using the above derived reliability measures the reliability of the individual machine tools over a specified time period and their respective mean time between failures can be determined. As mentioned previously the time period for all the forthcoming calculations would be 160 hours (1 month period).

5.2.1 CNC Lathe:

The time between failures for CNC lathe follows Weibull distribution (see Table 2). The probability density function f(t) of the 2 parameter Weibull distribution is given by

$$f(t) = \frac{\beta}{\theta^{\beta}} t^{\beta-1} e^{-(t/\theta)^{\beta}}$$

Using (12)

$$R_{LATHE}(t) = \int_{t}^{\infty} \frac{\beta}{\theta^{\beta}} t^{\beta-1} e^{-(t/\theta)^{\beta}} dt$$

Solving the above expression through integration by parts yields

$$R_{LATHE}(t) = e^{-(t/\theta)^{\beta}} \qquad (16)$$

Substituting the values of $\theta = 403.8257$ and $\beta = 1.809278$ obtained earlier for CNC lathe time between failures through maximum likelihood estimation into equation (16) yields

$$R_{LATHE}(160 hours) = 0.829196$$

The mean time between failures for the CNC lathe can be estimated from equation (15)

$$MTBF_{LATHE} = \int_{0}^{\infty} e^{-(t/\theta)^{\beta}} dt$$

Making the transformation $x = (t/\theta)^{\beta}$ in the above integral results in

$$MTBF_{LATHE} = \int_0^\infty \theta e^{-x} \frac{1}{\beta} (x^{1/\beta})^{1-\beta} dx$$

$$= \theta \frac{1}{\beta} \int_0^\infty x^{(1/\beta)-1} e^{-x} dx$$

By definition a gamma random variable $\Gamma(n)$ is defined by

$$\Gamma(n) = \int_0^\infty x^{n-1} e^{-x} dx$$

Using the above fact, the MTBF can be rewritten as

$$MTBF_{LATHE} = \theta \frac{1}{\beta} \Gamma(1/\beta)$$

Using the property of the gamma function, $n\Gamma(n) = \Gamma(n+1)$ the MTBF equation becomes

$$MTBF_{LATHE} = \theta \times \Gamma(1 + 1/\beta) \qquad (17)$$

Substituting the values of $\theta = 403.8257$ and $\beta = 1.809278$ obtained earlier for CNC lathe time between failures through maximum likelihood estimation into equation (17) yields

$$MTBF_{LATHE} = 359.029 hours$$

5.2.2 CNC Mill:

The time between failures for CNC milling machine follows Exponential distribution (see Table 3.5). The probability density function f(t) of the Exponential distribution is given by

$$f(t) = \lambda e^{-\lambda t}$$

Using (12)

$$R_{MILL}(t) = \int_t^\infty \lambda e^{-\lambda x} dx$$

Solving the above integral results in

$$R_{MILL}(t) = e^{-\lambda t} \qquad (18)$$

Substituting the values of $\lambda = 0.00279$ obtained earlier for CNC mill time between failures through maximum likelihood estimation into equation (18) yields

$$R_{MILL}(160 hours) = 0.686875$$

Using equation (15)

$$MTBF_{MILL} = \int_0^\infty e^{-\lambda t} dt$$

$$MTBF_{MILL} = \frac{1}{\lambda} \qquad (19)$$

Substituting the value of $\lambda = 0.00279$ in the above equation gives

$$MTBF_{MILL} = 425.4706 hours$$

5.2.3 CNC Drill/Bore:

The time between failures for CNC Drill follows Weibull distribution (see Table 3.5).Using the exact same procedure as developed for CNC lathe

$$R_{DRILL}(160 hours) = 0.846378$$

$$MTBF_{DRILL} = 404.5914 hours$$

5.2.4 CNC Grind:

The time between failures for the CNC grinding machine follows the smallest extreme value distribution. The probability density function (pdf), f(t) for the smallest extreme value distribution is given by

$$f(t) = (\frac{1}{\alpha}) e^{\frac{(t-\mu)}{\alpha}} e^{-e^{\frac{(t-\mu)}{\alpha}}}$$

The reliability function of the smallest extreme value can be derived using its relationship with the Weibull distribution. By definition if a random variable X has a Weibull time between failure distribution then its natural logarithm, T=ln(X) has a minimum extreme value distribution. To arrive at the reliability function of the smallest extreme value, let F(x) represent the cdf of the Weibull distribution and let G(t) represent the cdf of t=ln(x), and R(t) is the reliability function of T. Then by definition

$$G(t) = \Pr(T \le t) = \Pr(\ln(X) \le t) = \Pr(X \le e^t) = F(e^t)$$

As mentioned previously if a random variable X has a Weibull time between failure distribution then its natural logarithm, T=ln(X) has a minimum extreme value distribution. In other words the time between failures has a smallest extreme value distribution if and only if X=e^t has the Weibull distribution. So the above expression can be written as

$$F(e^t) = R_T(t) = R_X(e^t)$$

Using the reliability function of the Weibull distribution derived earlier the above expression can be rewritten as

$$R_X(e^t) = \exp[e^{-(t/\theta)^{\beta}}]$$

Simplifying the above expression yields the reliability function for the smallest extreme value distribution

$$R_{GRIND} = \exp[-e^{(t-\mu)/\alpha}] \qquad (20)$$

Substituting the values of α=251.628 and μ=707.3096 obtained earlier for CNC grinding machine time between failures through maximum likelihood estimation into equation (20) yields

$$R_{GRIND}(160 hours) = 0.892643$$

The mean time between failures for the smallest extreme value distribution is difficult to obtain, Ebeling (1997) provides the results of the MTBF expression for smallest extreme value distribution. Following Ebeling (1997),

$$MTBF_{GRIND} = \mu - \alpha\gamma \qquad (21)$$

, where γ=0.5772157 is the irrational Euler's constant defined by $\gamma = \lim_{n\to\infty}\left[\sum_{i=1}^{n}(1/i) - \log_e(n)\right]$

Substituting the values of α=251.628 and μ=707.3096 in the above equation results in

$$MTBF_{GRIND} = 562.136 hours$$

The manufacturing cell reliability can now be estimated since the necessary reliability measures for all the individual machine tools in the manufacturing cell have been determined.

5.3 Manufacturing cell reliability estimation:

As seen in figure 1 the crankshaft manufacturing/machining cell is comprised of four CNC machine tools: Lathe, milling machine, drilling/boring machine and a grinding machine. To produce a finished steel crankshaft, the crankshaft casting needs to be machined on all four machine tools in the manufacturing cell. The above case is very much similar to a system of four serially connected machines in which for the system to be reliable all four machines must be reliable. In other words, the system fails if any one of the four machines fails. So for the crankshaft manufacturing/machining cell all four machine tools must function reliably during the mission interval for the manufacturing cell, to produce the products. The reliability of the individual machine tools is a decreasing function of time. Furthermore the reliability of the manufacturing cell with serially placed machine tools can be no greater than that of the individual machine tools. More specifically the reliability of the manufacturing cell can be no greater than that of the least reliable machine tool in the manufacturing cell. For a serial system the system reliability is the product of the individual components reliability.

$$R_{MANUFACTURINGCELL} = R_{LATHE} \times R_{DRILL} \times R_{MILL} \times R_{GRIND} \qquad (22)$$

So the manufacturing cell reliability for 160 hours of operation/mission time would be the product of the reliability of the individual machine tools for 160 hours of operation. Substituting the values individual reliability of machine tools at 160 hours yields the manufacturing cell reliability.

$$R_{MANUFACTURINGCELL}(160 hours) = 0.430112$$

5.4 Manufacturing Cell Availability Estimation:

The instantaneous availability of a system with n serially connected components is given by

$$MTBF_{SYS} = \frac{1}{(1/MTBF_1) + (1/MTBF_2) + ... + (1/MTBF_n)}$$

So for a serially connected manufacturing cell with a lathe, drill, mill and grinder, the $MTBF_{SYS}$ reduces to

$$MTBF_{MANUFACTURINGCELL} = \frac{1}{(1/MTBF_{LATHE}) + (1/MTBF_{MILL}) + (1/MTBF_{DRILL}) + (1/MTBF_{GRIND})}$$

Substituting the MTBF of the individual machine tools in the above equation yields

$$MTBF_{MANUFACTURINGCELL} = 106.539529 hours \quad (23)$$

To compute the availability of the manufacturing cell, the mean time to repair for each of the individual machine tools is needed. Unfortunately, the manufacturing facility from which the data was collected does not record the repair time of the individual machine tools after failure occurs. This is because, most of the time, when failure occurs it results in replacement not repair. But the operators and the maintenance engineer based on their experience denote that the downtime/replacement time for their individual machine tools on an average is no more than 1 hour. So the repair time for each of the machine tool in the manufacturing cell will be assumed to be 1 hour for this analysis.

$$MTTR_{MANUFACTURINGCELL} = \frac{1}{(1/MTTR_{LATHE}) + (1/MTTR_{MILL}) + (1/MTTR_{DRILL}) + (1/MTTR_{GRIND})}$$

When the time to repair for each of the machine tool is assumed to be the same the above equation reduces to

$$MTTR_{MANUFACTURINGCELL} = \frac{1}{\sum_{i=1}^{n} MTTR_i}$$

Substituting the MTTR=1 hour in the above equation yields

$$MTTR_{MANUFACTURINGCELL} = 0.25 hours \qquad (24)$$

By definition the instantaneous availability is defined as

$$Availability = \frac{UPTIME}{(UPTIME + DOWNTIME)} \qquad (25)$$

Mathematically that is equivalent to

$$Availability = \frac{MTBF}{(MTBF + MTTR)} \qquad (26)$$

Substituting (32) and (33) in (35) gives the availability of transfer line

$$Availability_{MANUFACTURINGCELL} = 0.99765895$$

5.5 Reliability Estimation – Sensitivity Analysis:

Until now the Reliability of the manufacturing cell for 160 hours (1 month) of the plants operation has been considered. The manufacturing facility from which the data was collected has a daily preventive maintenance (Routine cleaning), a weekly preventive maintenance (Lubrication) and a monthly preventive maintenance (Replacement, Overhauling, etc.). So it is appropriate to obtain the reliability estimate for the above mentioned time periods to assess the probability of machine tools/manufacturing cell not failing in-between the scheduled maintenance operations.

Table 5.10: Manufacturing cell reliability estimation – Sensitivity analysis

Reliability at	Lathe	Mill	Drill	Grind	Manufacturi-ng Cell
8 hours	0.999171	0.981373	0.99903	0.939813	0.92064894
40 hours	0.984867	0.91027	0.98471	0.931935	0.82965521
160 hours	0.829196	0.686565	0.846378	0.892643	0.43011162

CHAPTER 6

Reliability/Availability assessment of Transfer Line

The transfer line that is considered in the study is a 15-station completely automated transfer line which machines engine block castings for lawnmowers. The transfer line performs various drilling, milling, boring and honing operations on the engine block castings. A transfer line is a linear network of machines or service stations. Material flows from outside the system to station1, then to station2, and so forth until it reaches station 15 after which it exits for assembly.

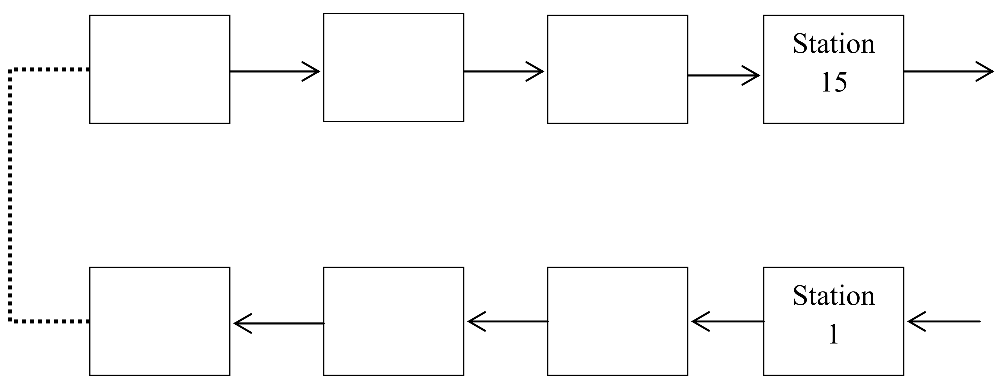

Figure 6.1: A 15 station palletized Transfer line

A transfer line is a complex manufacturing system comprising of mechanical, electrical, hydraulic and numerical control components. The engine block machined on the transfer line goes through each and every station in the transfer line in order to be machined completely. So for transfer line to operate reliably, all the stations in the transfer line must be available. Failure in any one of the stations will cause the line to shut down completely. From a reliability standpoint, the transfer line shown in figure 6.1 can be considered as a system comprised of machining stations placed in a serial configuration. As the number of stations along the transfer line increases, the probability of all stations being operational decreases. The system reliability is dependent on the reliability of the individual stations reliability. Mathematically the reliability of the transfer line is the product of the reliability of the individual stations. This implies that the reliability of the manufacturing cell can be no greater than that of the most unreliable station in the transfer line. Unfortunately, due to the lack of sufficient failure data from each of the stations and due to the fact that some failure data are not specific to a particular station but to the entire system, the transfer line is considered as a single system for the forthcoming calculations. This assumption is realistic because the transfer line is unavailable regardless of which station fails first.

Time between failure data from the transfer line:

The time between failures (TBF) of the transfer line, the time to repair (TTR) and the reasons for failure for the period of 3 years is given in Tables 5 below. The failure times are field/operational failures that were recorded when failures occurred and the failure times were not censored. Also the failures of the stations are independent of each other.

Table 6.1: Time between failures and time to repair for 3 years for a 15 station palletized Transfer line: (Source: Briggs and Stratton)

Time between Failures, hours	Time to repair, hours	Reason For failure
80	1.5	Proximity Switch Damaged
3	1	Bore Motor Failure
2	0.2	Broken Drill in Station 4
1	1	Dial cycling Failure
3	0.33	Internal Reamer broke
2	0.2	Internal Reamer broke
6	2.5	Outer door limit switch fault, outer cable broken
24	1.25	Broken Dial
5	0.08	Broken Intake Mandrel on Guide pin Press
4	0.75	Shaft rotation proximity faulting on station 1
5	0.32	Rotate shaft proximity faulting on station 1
1	1	Broken tap on station 8
0.5	0.48	Broken armature drill on station 5
25	0.24	Broken angular drill in station 6
8	0.16	Governor press failure
3	0.08	Broken exhaust guide pin on the press
4	1.24	Station 7 taper jammed
9	0.5	Dial table position failure
6	0.08	Broken intake reamer on coax
48	0.32	Broken starter drill on station 12
6	0.48	Station 5 valve not working
31	1	Lubrication Fault
82	0.4	Probe Fault on Station 5
22	0.08	Broken armature drill on station 5
88	1.2	Drill Coolant failure -Replacement of Valve for high pressure coolant
56	2	Drill Bushing crashed
26	2.5	Fixture failure on station 1
34	0.15	Broken Drill on Station 4
144	0.5	Broken Reamer

16	1.4	Taps jammed on station 5
108	0.25	Drilling machine failing to eject part. Replaced proximity switch
24	0.15	Broken Drill on Station 7
18	4	Station 8 dial refuses to return
110	2.5	Station 2 motor failure
120	0.2	Broken angular drill in station 6
54	0.18	Broken drill on station 4
56	0.5	Spindle change on station 2
150	3	Spindles spun out. Starter motor contact problem
3	2	Hydraulic line in the manifold busted
7	0.25	Reamer Busted
16	6	Exhaust cogs dill down at station 8
40	1.5	Milling tool broken
103	0.75	Counter timers busted
123	0.3	Broken drill in station 3
80	0.1	Foot mill switch stuck
115	0.2	Broken drill in station 7
201	1	Drilled into part and got struck at station 5
23	0.3	Broken drill at station 7
40	1	Two drills broken at station 5. Had to replace bushing
250	1.25	Relay switch fault
55	0.9	Milling machine switch box struck
25	0.25	Broken drilling machine manifold
20	3	Interlock switch and wire broken
246	0.2	Shear pin broken
21	0.2	Chamfer insert broken
35	0.5	Milling tool worn
253	0.1	Broken reamer tool
170	0.5	Slide pin shuttle broken
174	3	Tapping tool holder not operational
260	4	Governor bushing not pressing right
13	0.1	Taper tool broken
56	0.4	Belt broken on station 2
60	0.25	Limit switch shorted out
6	1.8	Fail to clamp on station 10
23	2	Milling machine down. Bad coil leading to blowing of fuses
26	2	Servo motor start up failure
16	2	Aluminum slag in piston bore stopped the transfer line
32	0.25	Coolant overflow

15	8	Control panel faulty. Replaced with new one
15	0.45	Crashed Mill. Part came of the fixture
20	0.5	Tapping tool broken
9	0.25	Station 7 not responding. Had to reset the whole system. Reason for failure not known
41	2.4	Governor press failure
34	0.3	Pin jammed in dowel press
15	0.4	Tapping tool broken
21	2	Part came of fixture in station 8 and crashed the mill
4	1.5	Part came of fixture in station 6 and crashed the mill
17	1	Governor bushing loose and broke the reamer
94	3	Governor press down
34	0.6	Multiple proximity faults on the boring machine
8	0.2	Error message. Misloaded part on station 2. Had to manually remove the misloaded part
3	0.2	Multiple misload faults. Had to adjust air valves on the dial
6	0.1	Station7 motor starter failed. Replaced with new one
3	0.3	Broken drill at station 4
26	0.3	Broken reamer at station 4
7	0.15	Broken mandrel and guide pin on the press
32	3	Dial down due to motor failure
14	0.3	Milling cutter crashed
12	1	Limit switch fault
8	1	Fuse burnt at station 6
3	3	Fuse burnt at station 5 and 4
35	0.2	Broken armature drill on station 5
4	0.25	Starter motor problem at station 7
14	1	Starter drill broke all the way down to the inserts and tool holder / had to replace starter drill tool holder inserts and drill bit
35	0.5	Spark plug drill broke at station 6
17	2	Broken wire at station 8
12	0.75	Air cleaner drill broke ate station 4
24	0.4	Broken drill at station 4
41	0.5	Broken clamp on station 3
10	0.5	Broken spark plug drill
36	0.25	Broken drill and tap for valve cover mount hole
43	0.15	Broken drill on station 4
56	0.4	Tap jam at station 6
2	0.2	Drill jam at station 5

25	0.2	Broken muffler mount tap on station 7
22	0.4	Broken drill on two spindle machine
61	0.4	Broken drill on station 4
75	3	Multiple tool breakage on Transfer line
26	0.2	Broken reamer on exhaust side
161	0.75	Broken wire in panel causing dial not to rotate
42	0.2	Broken drill on station 6
43	1	Broken drill and bushing on station 6
32	0.75	Fixture failed to clamp on station 2
24	3	Broken belt on the Transfer line
72	0.5	Fixture failed to clamp on station 2
27	0.2	Station 2 not moving
24	0.5	Broken oil drill drain on station 6
4	0.5	Crashed Mill on station 2
50	1.5	Transfer line dial crashed
42	0.5	Pneumatic valve failure
65	0.7	Taper jam at station 7

6.1 Identifying appropriate time between failures (TBF) distribution for the Transfer line

Form the recorded failure data of transfer line the Goodness of fit tests were conducted on Minitab© statistical software. The results of the tests for the failure data from the transfer line time between failure data are given below

Table 6.2: Minitab Goodness of fit tests for transfer line TBF

Distribution	Anderson-Darling Statistic	P value
Normal	11.288	<0.005
Box-Cox Transformation	0.384	0.390
Lognormal	0.697	0.067
3-Parameter Lognormal	0.619	*
Exponential	2.296	0.004
2-Parameter Exponential	2.372	<0.010
Weibull	0.713	0.063
3-Parameter Weibull	0.580	0.138
Smallest Extreme Value	16.729	<0.010
Largest Extreme Value	5.384	<0.010
Gamma	1.036	0.015
3-Parameter Gamma	0.845	*
Logistic	7.451	<0.005
Loglogistic	0.673	0.047
3-Parameter Loglogistic	0.728	*

From the above goodness of fit tests it is evident that none of the distributions except the Box-Cox transformation provide the appropriate fit for the time between failure data of the transfer lines. Box-Cox transformation could be used but it is not preferred in the field of reliability engineering, because the resulting reliability estimates would correspond to the transformed data not the true time between failures data. But it is essential to find an appropriate theoretical distribution for estimating the reliability/availability measures.

In order to improve the distributional fit, it was decided to ascertain if the data contained outliers. Some of the descriptive statistics from Minitab for the time between failure data from the transfer line is shown in Table 6.3.

Table 6.3: Minitab Descriptive Statistics for Transfer Line TBF

Minitab Descriptive Statistics: Transfer Line TBF

Variable	Mean	SE Mean	TrMean	StDev	Variance	CoefVar	Sum	Sum of Squares
TBF	44.97	5.11	37.15	56.26	3165.11	125.10	5441.50	624523.25

Variable	Minimum	Q1	Median	Q3	Maximum	Range	IQR	Mode	N for Mode
TBF	0.50	8.50	25.00	55.50	260.00	259.50	47.00	3	7

Variable	Skewness	Kurtosis
TBF	2.23	4.95

The skewness value of 2.23 for the TBF data indicates that the TBF distribution is positively skewed and there could be some extreme outliers present in the TBF data. Once the outliers are identified and removed the TBF data could be again checked for goodness of fit and an appropriate distribution to represent the TBF for the transfer line can be determined.

Extreme Outlier removal procedure:

The Boxplot is a useful graphical procedure to identify the outliers present in the data. A boxplot is graphical measure of variability. Devore (2007) lists the prominent features that Boxplots measure as (1) center, (2) spread, (3) the extent and nature of any departures from symmetry, and (4) identification of outliers, observations that lie unusually far from the main body of the data. The Boxplot of the time between failure data for the transfer line using Minitab is provided below, where the outliers are represented by * symbol. The outliers are the points that 1.5 standard deviations outside the Interquartile range. From the Boxplot it is evident that there are outliers only on the upper side of the interquartile range, due to large positive skewness.

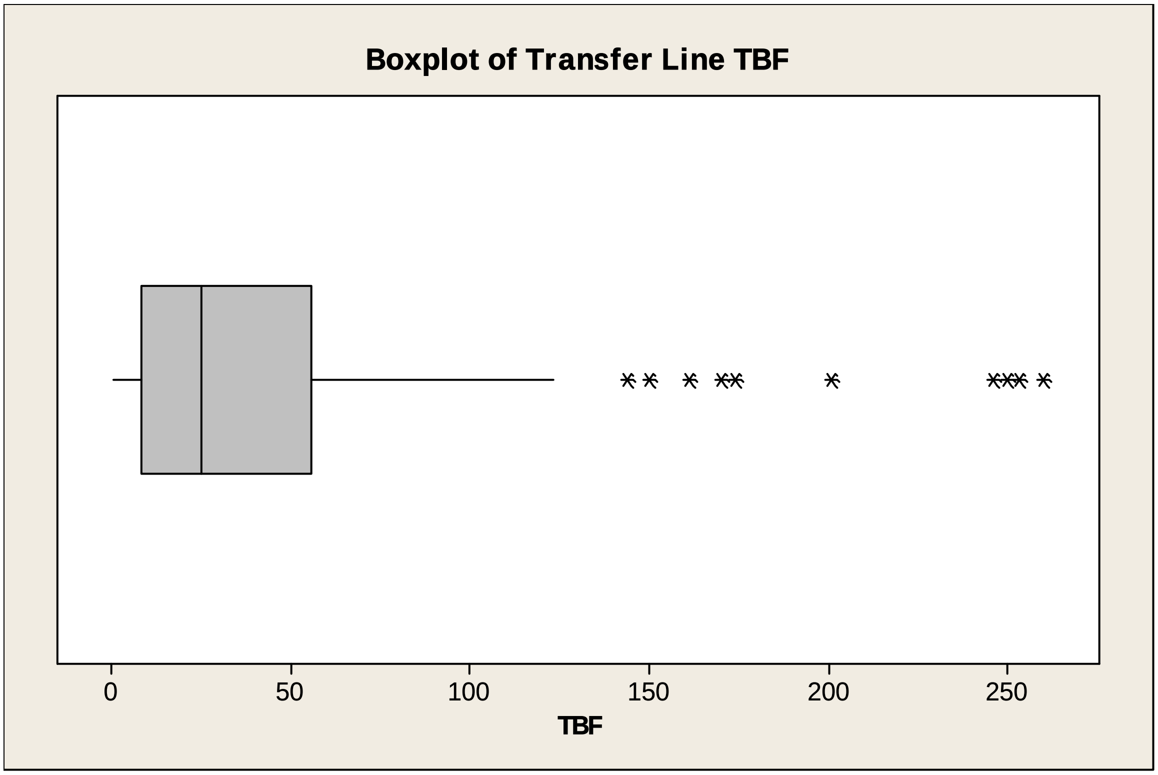

Figure 6.2: Minitab Boxplot for Transfer line TBF

By definition for the Boxplot any observation farther than 1.5 standard deviations from the interquartile range is an outlier. An outlier is extreme if it is more than 3 standard deviations from the interquartile range, and it is mild otherwise.

Unfortunately, Minitab does not differentiate mild outliers from extreme outliers in their Boxplot and the outliers in the above Boxplot consist of both mild and extreme outliers. It is not statistically justified to remove mild outliers from the data unless there are assignable causes. So for the following analysis, only the extreme outliers were removed from the original TBF data. A modified Boxplot with mild outliers differentiated from the extreme outliers is shown below.

Goodness of fit tests after removing extreme outliers:

The goodness of fit test for identifying an appropriate theoretical distribution for the transfer line time between failures after removing the extreme outliers was conducted using Minitab and the results of the goodness of fit tests after removing the extreme outliers form the time between failures data are given in table 6.3.

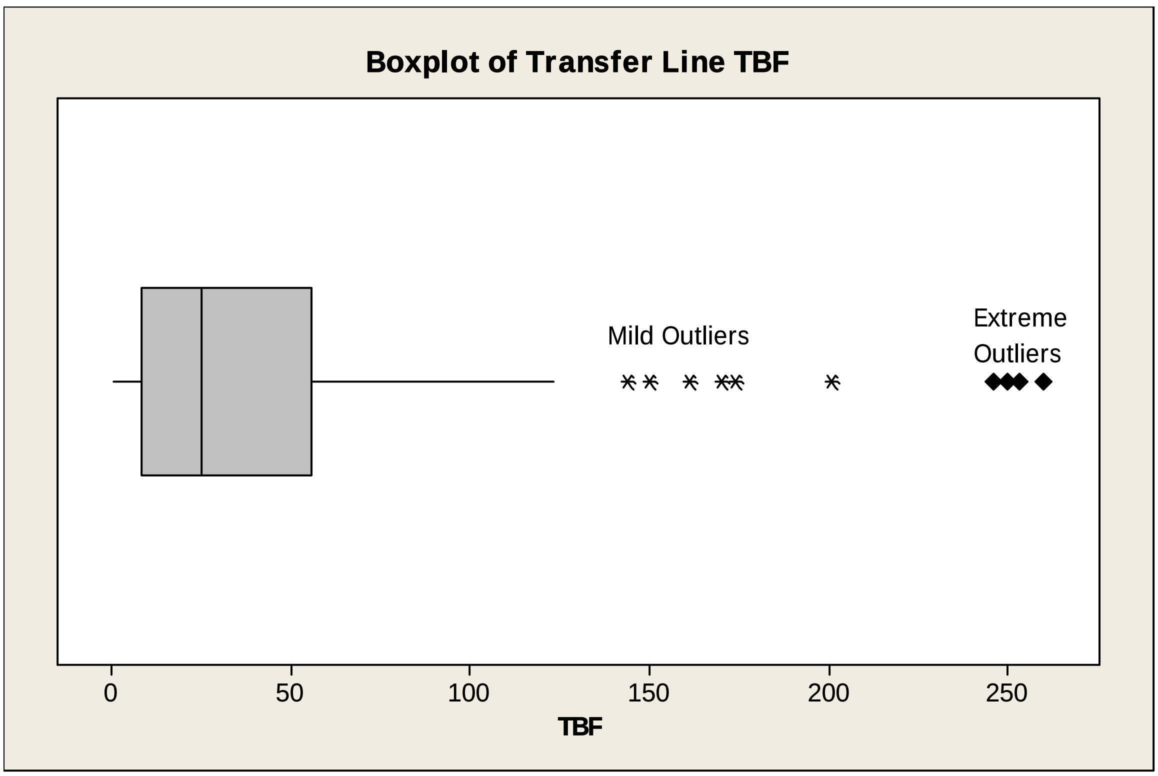

Figure 6.3: Modified Minitab Boxplot for Transfer line TBF

Table 6.4: Minitab Goodness of fit tests after removing extreme outliers

Distribution	Anderson-Darling Statistic	P value
Normal	8.243	<0.005
Box-Cox Transformation	0.410	0.339
Lognormal	0.973	0.014
3-Parameter Lognormal	0.791	*
Exponential	0.839	0.184
2-Parameter Exponential	0.892	0.144
Weibull	**0.473**	**0.243**
3-Parameter Weibull	0.401	0.387
Smallest Extreme Value	13.148	<0.010
Largest Extreme Value	3.618	<0.010
Gamma	0.576	0.171
3-Parameter Gamma	0.476	*
Logistic	5.501	<0.005
Loglogistic	0.910	0.010
3-Parameter Loglogistic	0.957	*

The above table 6.3 shows that the Weibull distribution has a sufficiently large P-value, which implies that the Weibull can be an appropriate model for representing the time between failures distribution of the transfer line. The three-parameter Weibull had a better fit than two-parameter Weibull but it was not selected because the minimum life δ was too small.

The Goodness of fit test were once again conducted by removing both the mild and extreme outliers (Mild = IQR$\pm 2\sigma$; Extreme = IQR$\pm 3\sigma$) from the time between failure data and the results are shown below

Table 6.5: Minitab Goodness of fit tests after removing both mild and extreme outliers

Distribution	Anderson-Darling Statistic	P value
Normal	6.075	<0.005
Box-Cox Transformation	0.466	0.249
Lognormal	1.268	<0.005
3-Parameter Lognormal	0.966	*
Exponential	0.396	0.647
2-Parameter Exponential	0.410	>0.250
Weibull	0.400	>0.250
3-Parameter Weibull	0.367	0.451
Smallest Extreme Value	10.500	<0.010
Largest Extreme Value	2.525	<0.010
Gamma	0.423	>0.250
3-Parameter Gamma	0.378	*
Logistic	4.111	<0.005
Loglogistic	1.163	<0.005
3-Parameter Loglogistic	1.181	*

From the above results of the goodness of fit tests the Exponential distribution has an excellent fit with a P-value of 0.647. Further the coefficient of variation with both the mild and extreme outliers removed from the TBF data is 0.998783 which is approximately equal to 1 (the theoretical CV for the Exponential density is 1) which confirms the fact that the TBF data when both the mild and extreme outliers are removed is exponentially distributed.

Removing all the mild outliers from the sample data is a controversial approach in Reliability Engineering the exponential distribution has too good a fit to be ignored when both the mild and extreme outliers are removed. Therefore the reliability parameters were estimated for the following two cases:

Case 1: The TBF has a Weibull distribution (Removing only the Extreme outliers)

Case 2: The TBF is exponentially distributed (Removing both mild and extreme outliers)

6.1.1 Case 1: The TBF has a Weibull distribution (Removing only the Extreme outliers):

Estimating the Weibull parameters β and θ using Maximum likelihood estimation (MLE):

The probability density function (pdf), f (t) of the 2-parameter Weibull distribution is given by

$$f(t) = \frac{\beta}{\theta^{\beta}} t^{\beta-1} e^{-(t/\theta)^{\beta}}$$

This implies that the probability element of the i^{th} failure time, t_i, is given by

$\frac{\beta}{\theta^{\beta}} t_i^{\beta-1} e^{-(t_i/\theta)^{\beta}} dt_i$ and hence the LF (likelihood function) is given by

$$L(\theta, \beta) = \prod_{i=1}^{n} \frac{\beta}{\theta^{\beta}} t_i^{\beta-1} e^{-(t_i/\theta)^{\beta}} = \left(\frac{\beta}{\theta^{\beta}}\right)^{n} \times \left[\prod_{i=1}^{n} t_i^{\beta-1}\right] \times e^{-\sum_{i=1}^{n}(t_i/\theta)^{\beta}} \quad (23)$$

Taking the natural log of (23) leads to

$$\text{Ln } L(\theta,\beta) = n[\ln(\beta) - \beta \ln(\theta)] + (\beta - 1)\sum_{i=1}^{n} \ln(t_i) - \sum_{i=1}^{n} (t_i/\theta)^{\beta} \quad (24)$$

The partial derivative of the Log-likelihood, ln(θ, β), wrt θ is given by

$$\partial[\text{Ln } L(\theta, \beta)]/\partial\theta = -n\beta/\theta - \frac{\partial}{\partial\theta}\left[\theta^{-\beta}\sum_{i=1}^{n}(t_i)^{\beta}\right] = -n\beta/\theta + \beta\,\theta^{-\beta-1}\sum_{i=1}^{n}(t_i)^{\beta} \xrightarrow{\text{Set to}} 0 \quad (25)$$

The solution to equation (25) is the MLE of θ which is given below.

$$\hat{\theta} = \left[\frac{1}{n}\sum_{i=1}^{n} t_i^{\hat{\beta}}\right]^{1/\hat{\beta}} \quad (26)$$

Equation (26) is the result that is needed to obtain the point MLE of the characteristic life θ, but the difficulty lies in the fact that unless the point MLE of the slope β is known the value $\hat{\theta}$ cannot be computed from Eq. (26). So the MLE of β has to obtained first by partially differentiating ln(θ,β) with respect to β.

$\xi(\beta) = \partial \ln(\theta,\ \beta)/\partial\beta = \dfrac{\mathbf{n}}{\beta} - n\ \ln(\theta) + \sum_{i=1}^{n} \ln(t_i) - [\sum_{i=1}^{n} \dfrac{\partial}{\partial\beta}(t_i/\theta)^{\beta}]$; bearing in mind that

$\dfrac{\partial}{\partial\beta}(t_i/\theta)^{\beta} = \dfrac{\partial}{\partial\beta} e^{\ln(t_i/\theta)^{\beta}} = \dfrac{\partial}{\partial\beta} e^{\beta \ln(t_i/\theta)}$ then it follows that

$$\partial[\text{Ln } L(\theta,\ \beta)]/\partial\beta = \frac{\mathbf{n}}{\beta} - n \ln(\theta) + \sum_{i=1}^{n} \ln(t_i) - \sum_{i=1}^{n} \left[(t_i/\theta)^{\beta} \times \ln(t_i/\theta) \right] \xrightarrow{\text{Set to}} 0 \qquad (27)$$

Equations (26) & (27) will have to be solved simultaneously in order to obtain the Maximum likelihood estimates of θ and β. Unfortunately, no closed-form exists for $\hat{\theta}$ and $\hat{\beta}$. Therefore, the solutions have to be obtained through trial and error that will make both partial derivatives ∂ln(θ, β)/∂θ in (25) and ∂ln(θ, β)/∂β in (27) almost equal to zero. The above task can be accomplished through the Newton-Raphson algorithm.

Estimating the Weibull parameters for the Transfer Line:

Using the above mentioned maximum likelihood estimation procedure the Weibull parameter estimates for the transfer line can be estimated using the time between failures data of the transfer line provided in Table 5. The parameter estimates is obtained using the following steps

(1) Arrange the time between failures data t_i's from smallest to largest, i.e. order the statistic, where the first order statistic represents the smallest time between failure data, the second order statistic the next smallest failure time and so on.

(2) Select an arbitrary value for β. A logical selection would be β greater than 1 because the CNC lathe is experiencing wear out failures as suggested from the data in Table 1. Elsayed (1996) also provides a good starting approximation of β which is given by $\hat{\beta}$ = 1.05/CV, where CV is the sample coefficient of variation from the failure data.

(3) Obtain the value of $\hat{\theta}$ using equation (26) and the arbitrary value of β. Substitute the values of θ and β in equation (27)

(4) Simultaneously solve for different values of $\hat{\beta}$ and $\hat{\theta}$ that makes equation (27) almost zero to obtain the estimates of β and θ for the given Weibull data. This can be solved Newton-Raphson algorithm using an appropriate software program.

The estimates of β and θ for the time between failures of the CNC lathe were obtained using the above mentioned steps. The Newton-Raphson method was solved using Microsoft Excel© Equation solver. The results are summarized below

System	Time between failures distribution	Estimates of the distribution Parameters
Transfer Line	Weibull	$\hat{\beta} = 0.935238; \hat{\theta} = 36.68059$

6.1.2 Case 2: The TBF is exponentially distributed (Removing both mild and extreme outliers):

Estimating the Exponential parameter λ using Maximum likelihood estimation (MLE):

The probability density function of an exponential random variable (pdf), f (t) is given by

$$f(t) = \lambda e^{-\lambda t} \tag{28}$$

This implies that the probability element of the i[th] failure time, t_i, is given by $\lambda e^{-\lambda t_i}$ dt_i and hence the likelihood function is given by

$$L(\lambda) = \prod_{i=1}^{n} \lambda e^{-\lambda t_i}$$

$$L(\lambda) = \lambda^n e^{-\lambda \sum_{i=1}^{n} t_i}$$

Taking natural logarithm on both sides

$$\ln[L(\lambda)] = \ln[\lambda^n e^{-\lambda \sum_{i=1}^{n} t_i}]$$

$$\ln[L(\lambda)] = n \ln(\lambda) - \lambda \sum_{i=1}^{n} t_i$$

Taking derivative with respect to λ

$$\frac{\partial}{\partial \lambda}[\ln(L(\lambda))] = \frac{n}{\lambda} - \sum_{i=1}^{n} t_i \xrightarrow{\textbf{Set to}} 0$$

$$\hat{\lambda} = \frac{n}{\sum_{i=1}^{n} t_i} \tag{29}$$

Equation (29) gives the maximum likelihood estimate for the exponential distribution with failure rate λ. So the failure rate λ for the Transfer line can be estimated using the time between failures data of Table 5. From the time between failures data from table 5 and using equation (29) the failure rate λ for Transfer line is estimated as

System	Time between failures distribution	Estimates of the distribution Parameters
Transfer Line	Exponential	$\hat{\lambda}$ =0.030323 per hour

6.2 Identifying appropriate time to repair (TTR) distribution for the Transfer line:

Form the recorded repair time data of transfer line (see Table 5) the Goodness of fit tests were conducted on Minitab© statistical software. The results of the test for the transfer line time to repair data are given below

Table 6.6: Minitab Goodness of fit test results for transfer line TTR

Distribution	Anderson-Darling Statistic	P value
Normal	10.628	<0.005
Box-Cox Transformation	1.204	<0.005
Lognormal	1.204	<0.005
3-Parameter Lognormal	0.777	*
Exponential	2.921	<0.003
2-Parameter Exponential	4.263	<0.010
Weibull	2.498	<0.010
3-Parameter Weibull	1.008	0.013
Smallest Extreme Value	17.596	<0.010
Largest Extreme Value	6.911	<0.010
Gamma	2.975	<0.005
3-Parameter Gamma	1.244	*
Logistic	8.103	<0.005
Loglogistic	1.379	<0.005
3-Parameter Loglogistic	0.927	*

From the above goodness of fit tests, it is evident that none of the afore mentioned distributions provide a good fit for the time to repair data from the transfer line. This might be due to the presence of some outliers as it was in the case of the time between failures data from the transfer line. The same approach of finding the extreme outliers as described previously for the TBF was employed. Some of the descriptive statistics from Minitab for the time to repair data from the transfer line is shown below

Minitab Descriptive Statistics: Transfer Line TTR

Variable	Mean	SE Mean	TrMean	StDev	Variance	CoefVar	Sum	Sum of Squares
TTR	1.001	0.111	0.850	1.218	1.485	121.68	121.170	299.503

Variable	Minimum	Q1	Median	Q3	Maximum	Range	IQR	Mode	N for Mode
TTR	0.080	0.250	0.500	1.250	8.000	7.920	1.000	0.2	14

Variable	Skewness	Kurtosis
TTR	2.71	10.28

Figure 6.4 Minitab descriptive statistics for Transfer line TTR

The above descriptive statistics indicates that the skewness value for the TTR data is 2.71, which indicates that the data is positively skewed and indicates the presence of some outliers in the TTR data. The Boxplot of the TTR data is shown in figure 6.4.

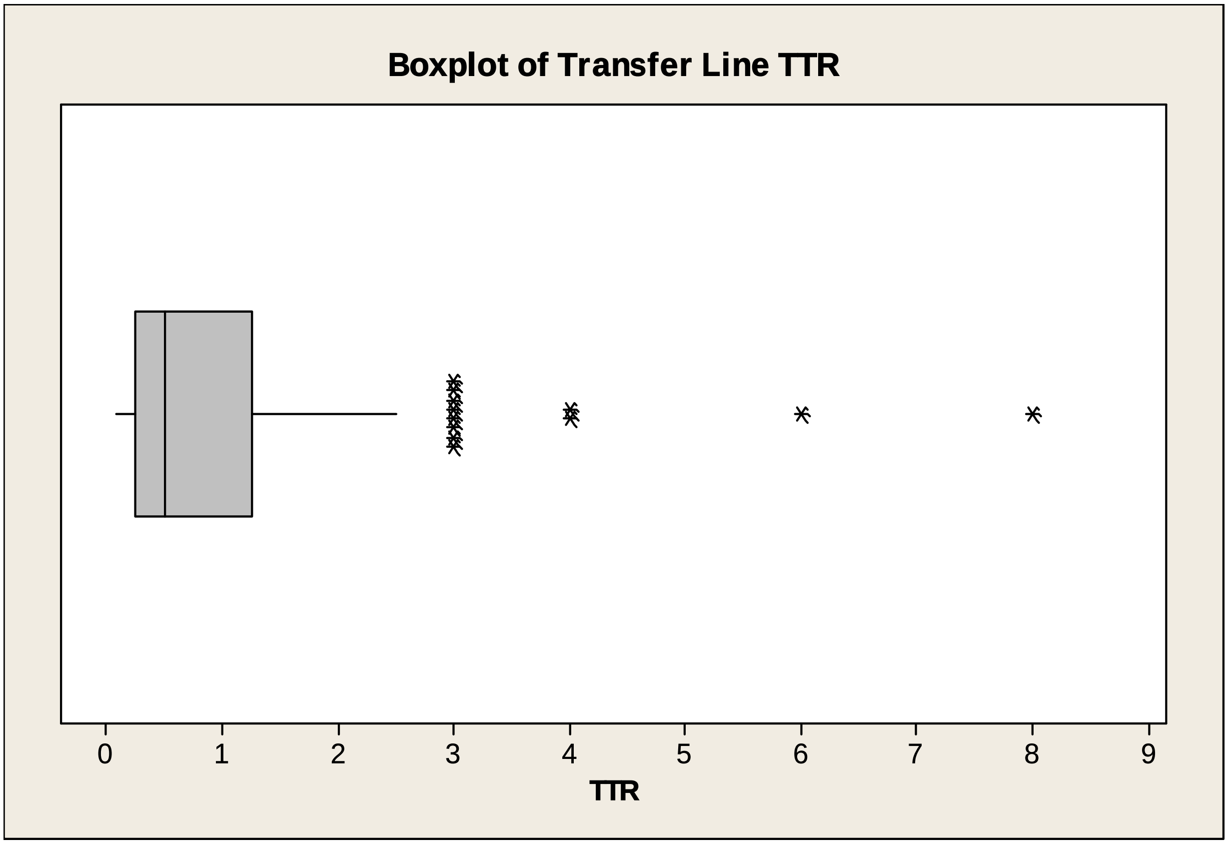

Figure 6.4: Minitab Boxplot for transfer line TTR

As mentioned previously Minitab plots outliers 1.5 standard deviations outside the interquartile range which includes both mild and extreme outliers. A modified Boxplot indicating both the mild (IQR±1.5σ) and extreme outliers (IQR±3σ) is shown below. To be more conservative and avoid trimming more data points IQR±2σ can be termed as mild outliers and IQR±3σ as extreme outliers.

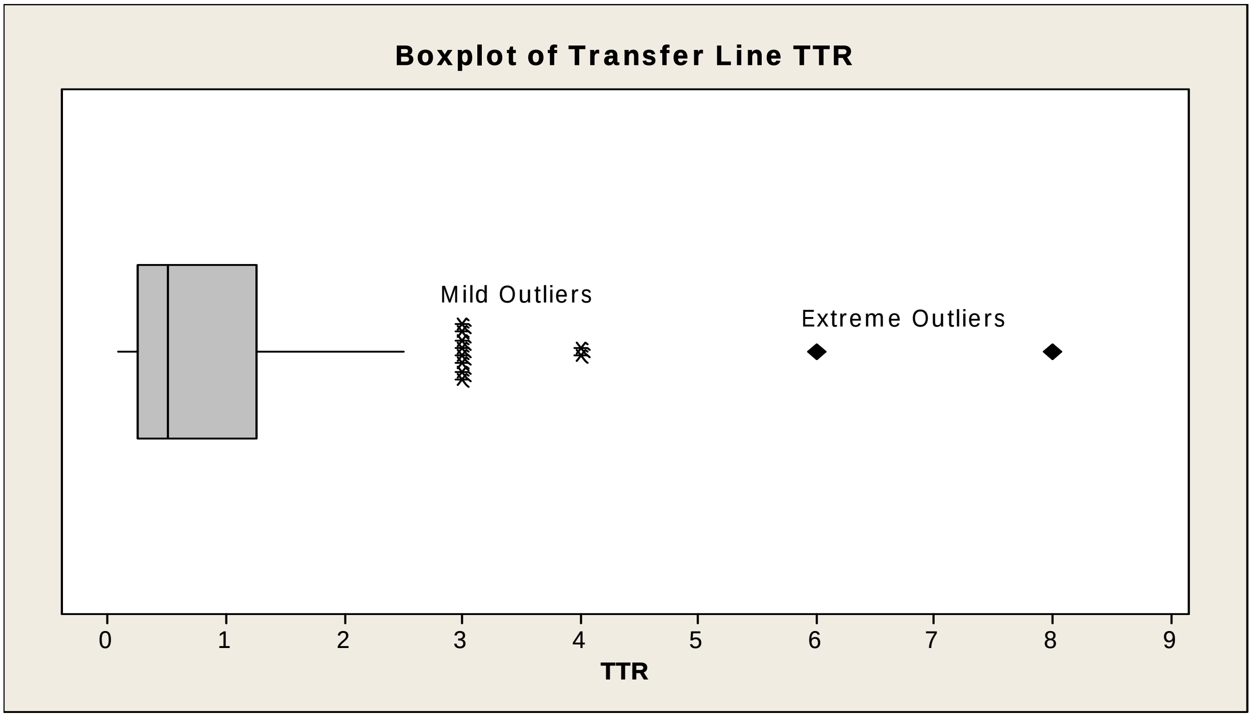

Figure 6.5: Modified Minitab Boxplot for transfer line TTR

Removing the extreme outliers and conducting the Goodness of fit again in Minitab yields the following results

Table 6.7: Minitab Goodness of fit tests for Transfer line TTR after removing extreme outliers

Distribution	**Anderson-Darling Statistic**	**P value**
Normal	9.514	<0.005
Box-Cox Transformation	1.299	<0.005
Lognormal	1.299	<0.005
3-Parameter Lognormal	0.915	*
Exponential	2.377	<0.004
2-Parameter Exponential	3.102	<0.010
Weibull	2.534	<0.010
3-Parameter Weibull	1.090	0.008
Smallest Extreme Value	12.281	<0.010
Largest Extreme Value	6.557	<0.010
Gamma	2.843	<0.005
3-Parameter Gamma	1.210	*
Logistic	7.806	<0.005
Loglogistic	1.456	<0.005
3-Parameter Loglogistic	1.028	*

After removing the extreme outliers, the data still does not fit into any statistical distribution. The goodness of fit test was conducted again by removing both mild and extreme outliers and the results are provided below.

Table 6.8: Minitab Goodness of fit tests for Transfer line TTR after removing mild and extreme outliers

Distribution	Anderson-Darling Statistic	P value
Normal	7.421	<0.005
Box-Cox Transformation	1.071	0.008
Lognormal	1.299	0.008
3-Parameter Lognormal	0.874	*
Exponential	2.194	0.006
2-Parameter Exponential	1.359	0.040
Weibull	2.138	<0.010
3-Parameter Weibull	0.954	0.018
Smallest Extreme Value	10.186	<0.010
Largest Extreme Value	4.686	<0.010
Gamma	2.191	<0.005
3-Parameter Gamma	0.982	*
Logistic	6.008	<0.005
Loglogistic	1.231	<0.005
3-Parameter Loglogistic	0.978	*

Even after removing mild and extreme outliers the time to repair data still does not follow any of the above mentioned theoretical distribution. In order to find a theoretical distribution for the time to repair data to estimate the reliability/availability measures, another approach is to compare the Skewness (the third standardized central moment) and Kurtosis (fourth standardized central moment - 3) from the sample data to the skewness and kurtosis of known theoretical distributions. The skewness and the kurtosis value of the TTR data from the above Minitab descriptive statistics are 2.71 and 10.28 respectively. The derived skewness and kurtosis of some of the theoretical distributions are given below.

Lognormal:

$$Skewness = \frac{e^{3\sigma^2} - 3e^{\sigma^2} + 2}{(e^{\sigma^2} - 1)^{1.5}}\ ;\ Kurtosis = \frac{e^{6\sigma^2} - 4e^{3\sigma^2} + 6e^{\sigma^2} - 3}{(e^{\sigma^2} - 1)^2}$$

Exponential:

Skewness = 2; Kurtosis = 6

Gamma:

$$Skewness = 2/\sqrt{n}\ ;\ Kurtosis = 6/n$$

Weibull:

$$Skewness = \frac{\Gamma(1+\frac{3}{\beta}) - 3\Gamma(1+\frac{2}{\beta})\Gamma(1+\frac{1}{\beta}) + 2\Gamma^3(1+\frac{1}{\beta})}{[\Gamma(1+\frac{2}{\beta}) - \Gamma^2(1+\frac{1}{\beta})]^{3/2}}$$

$$Kurtosis = \frac{\Gamma(1+\frac{4}{\beta}) - 4\Gamma(1+\frac{3}{\beta})\Gamma(1+\frac{1}{\beta}) + 6\Gamma(1+\frac{2}{\beta})\Gamma^2(1+\frac{1}{\beta}) - 3\Gamma^4(1+\frac{1}{\beta})}{[\Gamma(1+\frac{2}{\beta}) - \Gamma^2(1+\frac{1}{\beta})]^2} - 3$$

The value of the Skewness and Kurtosis for the above mentioned distributions from the TTR data is provided below

Distribution	Skewness	Kurtosis
Lognormal	11.84974627	603.8606093
Exponential	2	6
Gamma	1.990232029	5.941535293
Weibull**	3.017207731	10.13499102

**The value of β was computed for the TTR data from Table 6.1 using equations (26) and (27)

From the above table the theoretical Skewness and Kurtosis value of the Weibull distribution is the only one close to the skewness and kurtosis value from the TTR data in table 5 (2.71 and 10.27 respectively). Even though Weibull is a flexible distribution, it is impractical to find a value of β for which Skewness and Kurtosis will equal 2.71 and 10.27 respectively. But it is possible to find a value of β for which the theoretical value of skewness value would equal 2.7114. Through trial and error, the $\hat{\beta}$ value for which the theoretical Weibull skewness is equal to 2.7114 is computed to be 0.81923.

Substituting $\hat{\beta}$=0.81923 equation (26) gives the value $\hat{\theta}$= 0.907962.

System	Time to repair distribution	Estimates of the distribution Parameters
Transfer Line	Weibull	$\hat{\beta}$=0.81923; $\hat{\theta}$= 0.907962

6.3 Estimating Reliability of the Transfer Line:

6.3.1 Case 1: Using Weibull TBF Distribution:

The time between failures for the transfer line follows Weibull distribution (see Table 5). The probability density function f(t) of the 2 parameter Weibull distribution is given by

$$f(t) = \frac{\beta}{\theta^{\beta}} t^{\beta-1} e^{-(t/\theta)^{\beta}}$$

Using (12)

$$R_{TRANSFERLINE}(t) = \int_{t}^{\infty} \frac{\beta}{\theta^{\beta}} t^{\beta-1} e^{-(t/\theta)^{\beta}} dt$$

Solving the above expression through integration by parts yields

$$R_{TRANSFERLINE}(t) = e^{-(t/\theta)^{\beta}} \tag{30}$$

Substituting the values of θ = 36.68059 and β = 0.935238 obtained earlier for transfer line time between failures through maximum likelihood estimation into equation (30) yields

$$R_{TRANSFERLINE}(160 hours) = 0.018966$$

The mean time between failures for the CNC lathe can be estimated from equation (30)

$$MTBF_{TRANSFERLINE} = \int_{0}^{\infty} e^{-(t/\theta)^{\beta}} dt$$

Making the transformation x = $(t/\theta)^{\beta}$ in the above integral results in

$$MTBF_{TRANSFERLINE} = \int_{0}^{\infty} \theta e^{-x} \frac{1}{\beta} (x^{1/\beta})^{1-\beta} dx$$

$$= \theta \frac{1}{\beta} \int_0^\infty x^{(1/\beta)-1} e^{-x} dx$$

By definition a gamma random variable $\Gamma(n)$ is defined by

$$\Gamma(n) = \int_0^\infty x^{n-1} e^{-x} dx$$

Using the above fact, the MTBF can be rewritten as

$$MTBF_{TRANSFERLINE} = \theta \frac{1}{\beta} \Gamma(1/\beta)$$

Using the property of the gamma function, $n\Gamma(n) = \Gamma(n+1)$ the MTBF equation becomes

$$MTBF_{TRANSFERLINE} = \theta \times \Gamma(1 + 1/\beta) \tag{31}$$

Substituting the values of θ = 36.68059 and β = 0.935238 obtained earlier for CNC lathe time between failures through maximum likelihood estimation into equation (31) yields

$$MTBF_{TRANSFERLINE} = 37.82796 hours \tag{32}$$

As mentioned previously the time to repair (TTR) data follows a Weibull distribution. Using the previously obtained value of β = 0.81923 in equation (31) yields

$$MTTR_{TRANSFERLINE=} 1.01183 hours \tag{33}$$

By definition the instantaneous availability is defined as

$$Availability = \frac{UPTIME}{(UPTIME + DOWNTIME)} \tag{34}$$

Mathematically that is equivalent to

$$Availability = \frac{MTBF}{(MTBF + MTTR)} \tag{35}$$

Substituting (32) and (33) in (35) gives the availability of transfer line

$$Availability_{TRANSFERLINE} = 0.970090401$$

6.3.2 Case 2: Using Exponential TBF distribution:

The probability density function f(t) of the Exponential distribution is given by

$$f(t) = \lambda e^{-\lambda t}$$

Using (12)

$$R_{TRANSFERLINE}(t) = \int_t^{\infty} \lambda e^{-\lambda x} dx$$

Solving the above integral results in

$$R_{TRANSFERLINE}(t) = e^{-\lambda t} \tag{36}$$

Substituting the values of $\lambda = 0.030323$ obtained earlier for the transfer line time between failures through maximum likelihood estimation into equation (36) yields

$$R_{TRANSFERLINE}(160 hours) = 0.007815$$

Using equation (15)

$$MTBF_{TRANSFERLINE} = \int_0^{\infty} e^{-\lambda t} dt$$

$$MTBF_{TRANSFERLINE} = \frac{1}{\lambda} \tag{37}$$

Substituting the value of λ = 0.030323 in the above equation gives

$$MTBF_{TRANSFERLINE} = 32.97788 hours \tag{38}$$

From (33)

$$MTTR_{TRANSFERLINE=} 1.01183 hours$$

Substituting (38) and (33) in equation (35) yields

$$Availability_{TRANSFERLINE} = 0.970231$$

The above transfer line availability is very close to the availability computed assuming Weibull time between failures. So regardless of whether the TBF of the transfer line follows a Weibull distribution or an Exponential distribution, the availability of the transfer line is no greater than 97% approximately.

CHAPTER 7

Results

The Weibull distribution was found suitable in most of the cases to represent the time between failures distribution of CNC machines used in manufacturing cell. Goodness of fit tests was used to identify the appropriate distributions for time between failures of CNC machines used in the manufacturing cell. When the data contained outliers, Goodness of fit tests failed to identify an appropriate distribution to represent time between failures of Transfer Lines. To identify an appropriate time between failure distributions for transfer line, both mild and extreme outliers in the data was identified and removed. Goodness of fit test was conducted for two cases – removing only mild outliers and removing both mild and extreme outliers. Weibull distribution had a good fit after removing the mild outliers from transfer line TBF data and exponential distribution gave an excellent fit after removing both mild and extreme outliers from the Transfer Line TBF data. Reliability measures were calculated for both cases and the reliability measures was not significantly different for the two cases considered. Goodness of fit test failed to identify an appropriate distribution, even after removing mild and extreme outliers from the time to repair data of the Transfer Line. Skewness and Kurtosis values were used identify an appropriate time to repair distribution. Weibull distribution was found suitable to represent the time to repair distribution of the Transfer Line.

After identifying the appropriate time between failures and time to repair distributions, the necessary reliability measures were estimated for manufacturing cell and transfer line. Once the necessary reliability measures were obtained, availability of manufacturing cell and transfer line was determined. The crankshaft manufacturing cell considered in this thesis was available 99.76% of the time and the Transfer Line was available 97.06% of the time.

CHAPTER 8

Conclusion

The statistical reliability model proposed in this thesis is simple and could be employed by manufacturing organizations to estimate availability and MTBF of their machine tools/transfer lines. Collecting field failure data is essential for assessment and improvement of system reliability. Selecting an appropriate distribution for failure data is essential in predicting the reliability measures. The results of this thesis shows that the Weibull distribution could be used most of the time to represent time between failures and repair time distribution of machine tools and transfer lines. Once the time between failures distribution is identified, all the other reliability/availability measures could be derived using suitable statistical estimation techniques.

Availability is a function of MTBF and MTTR. To increase availability the MTBF should be increased and/or the MTTR should be reduced. MTBF can be increased by improving the reliability of the components/system hence reducing frequency of failures whereas MTTR can be reduced by proper maintenance techniques, proper training and by employing preventive/predictive maintenance.

To improve the reliability of manufacturing systems, the critical components affecting the system reliability should be identified and failure mode and effect analysis (FMEA) should be conducted for each of these critical components. Field failure data should be collected for each of the failure modes. With the above information, periodic replacement and preventive & predictive maintenance can be scheduled to improve the system reliability. This proposed method is effective in improving system reliability, but the above methodology could be very complicated to implement in transfer lines and flexible manufacturing systems since the number of critical components and their failure modes is quite large.

Preventive maintenance can reduce the frequency of failures, but it is often difficult to determine the proper maintenance interval. Preventive maintenance can be termed as scheduled downtime. Preventive maintenance performed too frequently can actually decrease availability. Whenever the complexity of the system increases, the complexity of maintainability along with the cost involved in maintenance also increases. Even though the operations of the transfer lines and flexible manufacturing systems are entirely automatic, the maintenance of those complex systems is still completely manual. Unlike manufacturing cells in which operators can perform maintenance and basic repairs, the transfer line requires specialized maintenance personnel for repair and routine maintenance.

Manufacturing cells could be considered more reliable than transfer lines, but it is unfair to compare the reliability of manufacturing cell with that of transfer lines because the transfer line has much more components/stations than manufacturing cells. But from a maintainability standpoint, manufacturing cells provide the advantage of having simple CNC machine tools which are much easier to maintain and repair than transfer lines. In addition, operators in manufacturing cell can perform basic repair operations on machine tools in manufacturing cell whereas the transfer line requires trained maintenance technicians to perform repairs on transfer lines. In conclusion, an increase in automation requires higher reliability and maintainability requirements to increase manufacturing uptime.

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APPENDIX

Lean tools and manufacturing waste

The 8 Deadly Manufacturing Waste:

(1) **Defects** – Producing products that do not meet customer or design specifications. Defects may lead to rework or scrap, which represents the waste of material, time and energy involved in making and correcting defects.

(2) **Overproduction** – Producing products that are not required by the customers yet. Considered the worst manufacturing waste as overproduction leads to the waste of inventory, which has to be stored, accounted and protected.

(3) **Waiting** – The waste of waiting for materials, waiting for machines to process the part and waiting for broken machine to get repaired. It is considered a waste because the operator or employee is still paid for the period of time spent in waiting.

(4) **Not utilizing people** – Dennis (2002) defines wasted talent as disconnects within or between the company and its customers and suppliers. These inhibit the flow of knowledge, ideas, and creativity, creating frustration and missed opportunities.

(5) **Excessive Transportation** – Waste of excessive transportation caused by poor layout/facility design, keeping processes far away from each other, overly large equipment. This waste represents inefficient use of factory space.

(6) **Excessive Inventory** – The waste of excess inventory is related to keeping unnecessary raw materials, WIP and finished products. Excess inventory has to be stored, accounted and protected which requires space, energy, money and labor.

(7) **Excessive Motion** – Excessive motion represents a loss of productivity due to poor occupational ergonomics. Quality and productivity of operator is reduced when there is awkward postures and repetitive motion involved in the task.

(8) **Extra processing** – This waste is related to doing more than what the customers desire. This is often caused by loss of information flow between marketing, design, engineering, and production department.

Lean tools:

(1) **Manufacturing cells** – See section 3.1, page 17

(2) **Pull system/Kanban** – To produce an item only when the customer asks for it. This production control is achieved through Kanban cards and carts, which avoids production in the upstream processes until the downstream process requires it.

(3) **Poka–yokes** – Defect prevention devices built within the equipment which prevents the operators from producing defects/ human errors.

(4) **Quick changeover** – A structured methodology (pioneered by Shigeo Shingo) of converting internal elements (processes that can be performed only when machine is stopped) into external elements (processes which can be performed when equipment is running) to reduce setup/changeover time.

(5) **JIDOKA** – Sensible automation of separating operator's task from machine task, which enables the operator to leave the machine when running, to perform other value added tasks.

(6) **Value stream mapping** – A high level process mapping used to identify the non value added activities in all the steps required to bring a product to a customer.

(7) **5S** – A system of workplace standardization and housekeeping aimed at reducing the non-value added activities in the workplace.

(8) **Total productive maintenance (TPM)** – Methodology to increase overall equipment effectiveness and achieve zero downtime by measuring the six big losses, prioritizing problems, and solving the problem through autonomous maintenance.