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Chapter 1

MANUFACTURING PROCESS PLANNING BASED ON RELIABILITY ANALYSIS OF MACHINES AND TOOLS

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ABSTRACT

In many manufacturing industries, planning and scheduling are decision-making processes used as important roles in procurement and production. The planning and scheduling functions in a company rely on mathematical techniques and heuristic methods to allocate resources such as machine-tools, to execute the activities to comply with the production planning requirements. Objectives can take many different forms, such as minimizing the time to complete all activities, minimizing the number of activities or maximizing the process reliability. The manufacturing process must consider its dynamic as a mechanism to avoid non-conforming parts.

A manufacturing process is defined as a sequence of pre-established operations, aiming at the production of a specific part. The process reliability is depended on the operation sequence and their reliabilities. The operation reliability is a statistical relation between cutting tool, operator and machine-tool reliability. Machines often have to be reconfigured or cleaned between jobs. This is known as a changeover or setup. The length of the setup depends on the job just completed and on the one about to be started.

This chapter presents machining process planning based on reliability analysis of machines and tools. It is possible to determine the running time for each tool involved in the process by obtaining the operations sequence for the machining procedure. The

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cutting tool life can be modeled with a probability function representing the chance that a critical wear magnitude is achieved in a given time period. The machine-tool reliability can be modeled according to an exponential distribution, which parameter is dependent on the electrical motor, spindle and bearings failure rates. Aiming at keeping the manufacturing process reliability higher than a minimum value, defined in the process planning, an algorithm to define the cutting tool change period is presented.

1. INTRODUCTION

Reliability is defined as the probability that a given product will successfully perform a required function without failure, under specified environmental conditions, for a specified period of time.

Deficiencies in design and manufacturing planning affect all items produced and are progressively more expensive to correct as development proceeds. It is therefore essential that design and manufacturing disciplines be used to minimize the possibility of failure and to allow design deficiencies to be detected and corrected as early as possible. The reliability concepts are usually applied in the product design process but its use in the manufacturing process planning is not so common.

In 2000, Savsar presented a stochastic model to determine the performance of a Flexible Manufacturing Cell under random operational conditions, including random failures of cell components (machine tool and robot) in addition to random processing times, random machine loading and unloading times, and random pallet transfer times [1].

A methodology based on Petri nets was used for identifying the failure sequences and assessing the probability of their occurrence in the manufacturing system. The method employs Petri net modeling and reachability trees constructed based on the Petri nets. The methodology is demonstrated on an example of an automated machining and assembly system [2].

Manufacturing processes planning is an activity executed by any mechanical industry in order to define the processes and the tools that will be used to manufacture specific parts and to assembly a specific system. Usually that activity involves the theoretical and experimental evaluation of machine tools' accuracy and resolution, tools performance, and once the manufacturing processes is defined, a try out is executed, aiming the definition of the processes capability. The basic goal of processes planning is to define a sequence of manufacturing activities to produce a mechanical part according to design dimensional and geometrical tolerances.

Considering any manufacturing process as a system, composed of machine tools, tools, and tools operational conditions, its reliability can be evaluated using the traditional reliability concepts, aiming the definition of a manufacturing process failure probability, taking in view the occurrence of failures in the components of the systems mentioned above.

2. PROCESS PLANNING IN MANUFACTURING SYSTEMS

The manufacturing process planning is a complicated and combined problem, therefore it is necessary to divide the tasks into hierarchical levels, [3]. In this manner, the process plan is defined successively, step by step, up to down. The ‘up to down’ term means that the planning process progresses from the complex tasks to the simpler and the process plan becomes more detailed and concrete.

In technical literature there is no unified standpoint about the number and the tasks of these planning levels. Groover [4] divides the whole process planning as follows: (1) preliminary process planning, (2) planning the sequence of operations, (3) operations planning, (4) operation elements planning.

The preliminary process planning is the highest level of manufacturing process planning, the strategy of the manufacturing. According to those authors, the tasks of the process planning are as follows:

- Collecting the technological data for the process planning of the blank manufacturing, the part manufacturing and the assembly; rationalizing of manufacturing process; preparing of manufacturability and assembly of the correct part, assembly and blank design documentation.
- Determining the strategy of process planning which means the selection of manufacturing systems and actual manufacturing variant.
- Analyzing the manufacturing tasks, estimation of manufacturing cost and time data.

Based on the above mentioned definitions, it is possible to observe that some information is not considered by those authors, such as:

- The manufacturing operation sequence must considerer the time to produce a given lot of parts. The operational time is important once the machine tool operational condition and the tool wear are time-dependent and can affect the manufactured part precision.
- The tool and machine tool reliability deal with modeling the time dependent performance of those components and can allow the prediction of possible failures in the manufacturing processes in advance. Those failures are related to the loss of geometrical and dimensional precision of the manufactured parts. The use of reliability concepts can anticipate problems in manufacturing and together with the traditional quality control procedure (usually based on Quality Control Charts), would improve the early detection of possible manufacturing process loss of quality.
- The use of reliability concepts can also be used to detect possible weaknesses in the manufacturing process associated with potential failures in machine tool that could significantly affect the process reliability.

Based on the previous analysis, it is important to add reliability concepts to manufacturing process planning for the prediction of loss of accuracy in the produced parts associated to time-dependent machine and tool degradation phenomena. In order to correct add reliability concepts in manufacturing planning activities, the next section will discuss manufacturing planning functions and reliability concepts.

2.1. Process Planning Function

The functions of the process planning activities are related to the definition of the manufacturing and assembly sequence of a given product design. In order to achieve that goal, the process planning function is dependent on the available resources in the manufacture plant (including machine tools, cutting of forming tool characteristics and labor skill) and on the dimensional and/or geometrical tolerance of the parts.

Nevertheless, the general function of the manufacturing planning is to define the optimized sequence of process aiming at producing and assembling a given set of parts to compose a product. The manufacturing process planning function also includes the definition of the basic parameters of each manufacturing process used for each part, including tool selection, machine tool operational conditions, quality controls methods and process capability analysis. Also, in a broad way, the manufacturing planning process can also include the manufacturing plant capacity estimate and the development of manufacturing patterns.

Rozenfeld [5] proposed to divide the manufacturing process planning functions in two major tasks: Macro Planning and Detailed Planning as shown in Figure 1. In the first task, the manufacturing sequence is defined based on plant restrictions and in the second task, each manufacturing process is detailed, including machine tool, cutting or forming tool selection and estimative of manufacturing time.

Rezende [6] proposes another view of the manufacturing process planning for a given part. The method can be considered complementary to the method proposed by Rozenfeld [5]. The first step corresponds to a general manufacturing planning for the part where the manufacturing steps for part production are defined according to design specifications. The second step corresponds to a detailed manufacturing planning where each manufacturing step is specified; including machine tool and tools, selections and geometrical and dimensional tolerance studies are executed in order to define jigs and fixtures selections. In Table 1, the method basic steps are presented.

It is important to notice that those methods do not consider the possible aging effects associated with the machine tools that could affect their accuracy and consequently the parts dimensional and geometrical tolerances. For those methods, the machine tools have the same performance during its operational life.

Furthermore, during cutting of forming tool selection, those methods consider the possible aging effects presented by the tools, but in a deterministic manner. The manufacturing planner frequently uses empirical relations (such as the Taylor Eq. for cutting tool) to estimate the tool life aimed at controlling the tool wear.

The reliability concepts can be used to predict the time-dependent aging effects acting on tools and machine tools aimed at predicting the frequency of failure of the manufacturing process associated with equipment failure. The reliability concepts can also be used to estimate tool wear aimed at defining tool change time during manufacturing planning.

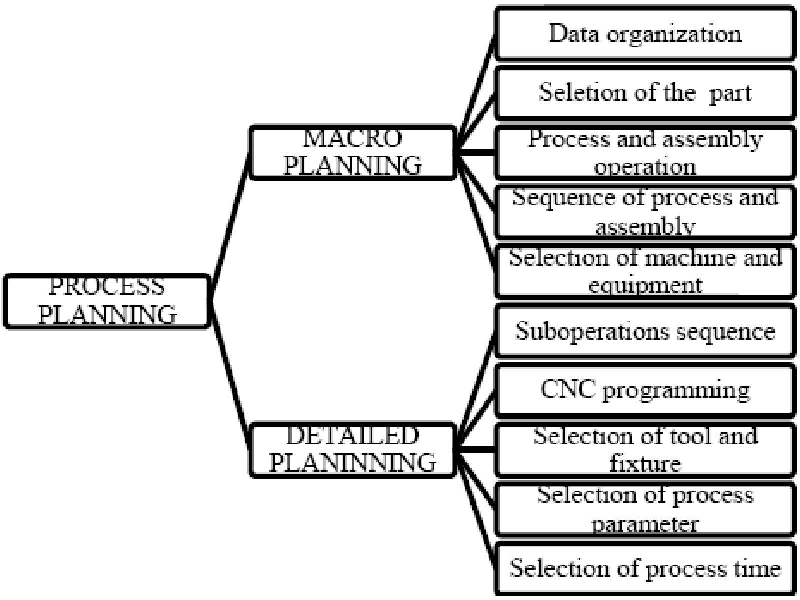


Figure 1. Manufacturing Process Steps [5].

Table 1. Manufacturing Process Planning Steps [6]

Step	Sub-Step	Characteristics under Analysis	
General Process Planning	Part design analysis	Part geometry	
		Basic surfaces definitions	
		Material and heat treatment	
		Part dimensions	
	Preliminary machining methods	Surface geometry	
		Surface dimensions	
		Surface finishing requirements	
		Part weight and size	
		Material and heat treatment	
		Production volume	
	Definition of manufacturing process steps	Operations	Rough
			Half-finish
			Finish
	Operations grouping	Tools and Machine Tools capability	
		Machine tools availability	
		Set up time and operation time	
		Part size and weight	
		Production volume	
	Heat treatment grouping	Heat treatment	Normalizing
			Annealing
			Quenching
			Temper
			Others
		Part characteristics	
		Finishing	
	Auxiliary manufacturing steps	Inspection	
		Cleaning	

Table 1. (Continued)

Step	Sub-Step	Characteristics under Analysis	
Detailed process planning	Machine tools selection	Machine precision x part required precision	
		Machine working area	
		Machine power	
		Machine capacity x Part production volume	
		Machine availability	
	Machine tool selection	Tool	Geometry
			Material
		Machining process	
		Machine tool selection	
		Part surface finishing precision	
	Jigs and fixtures selection	Set up time	
		Operational costs	
Detailed process planning	Reference surfaces selection	Reference type	Design
			Manufacturing
			Measuring
			Assembly
		Design dimensions and tolerances	
		Manufacturing dimensions and tolerances	
	Machining dimensions and tolerances	Prior operation surface finishing	
		Machining conditions	
	Cutting conditions selection	Cutting depth	Machine tool power
			Cutting tool characteristics
			Part stiffness
			Fixture
		Feed rate	Surface finishing
		Cutting speed	Production volume
			Production costs
	Reference time	Machining time	
		Set up time	
	Process planning documents	Process sequence	
		Detailed operation plan	

3. RELIABILITY CONCEPTS

Reliability has many connotations. In general, reliability is defined as the probability that a given product will successfully perform a required function without failure, under specified environmental conditions, for a specified period of time [7].

A reliability measure is needed to answer questions such as: “How long will the equipment last without breakdown?”; “How long a warranty can be given for new equipment?”. In any given equipment population, the life length is a random variable. When questions must be answered regarding the behavior of such random variables, it is necessary to use probability, probability distributions, averages and measures of variability.

It must be realized, while defining the reliability of a piece of equipment, that the function the equipment is expected to perform must be clearly specified along with a definition of what constitutes a failure [8].

Furthermore, the conditions under which the piece of equipment is expected to perform the required function must also be clearly specified. Reliability under one set of operating conditions may be different from that under another.

Finally, reliability must be expressed as a function of time. At any specified time, a certain proportion of the equipment population will continue to successfully perform the required function without failure. Reliability can represent this proportion of the population that survives beyond the specified time [7].

Probably the single most used parameter to characterize reliability is the mean time to failure (or MTTF). It is just the expected or mean value of the failure time, expressed according to Eq. (1):

$$MTTF = \int_0^\infty R(t)dt \tag{1}$$

where:

$R(t)$ reliability at time t

T time period, usually expressed in hours for pieces of equipment in power plants [h]

Random failures (represented by the exponential probability function) constitute the most widely used model for describing reliability phenomena. They are defined by the assumption that the rate of failure of a system is independent of its age and other characteristics of its operating history. In that case, the use of mean time to failure to describe reliability can be acceptable once the exponential distribution parameter, the failure rate, is directly associated with MTTF [9].

When the phenomena of early failures, aging effects, or both, are presented, the reliability of a device or system becomes a strong function of its age.

The Weibull probability distribution is one of the most widely used distributions in reliability calculations involving time-related failures. Through the appropriate choice of parameters, a variety of failure rate behaviors can be modeled, including constant failure rate, in addition to failure rates modeling both wear-in and wear-out phenomena [9].

The two-parameter Weibull distribution, typically used to model wear-out or fatigue failures is represented by the following Eq.:

$$R(t) = e^{-\left(\frac{t}{\eta}\right)^{\beta}} \tag{2}$$

where:

$R(t)$ reliability at time t

t time period, usually expressed in hours for pieces of equipment in power plants [h]

β Weibull distribution shape parameter

η Weibull distribution characteristic life [h]

The life time distribution of a piece of equipment is the basic information from which all measures of reliability are evaluated. It is the distribution of the length of life of all items in the population of a piece of equipment. The distribution can be estimated from a set of sample life data taken from the population. Such data can be generated by testing a sample in the laboratory, or, as usually done for large pieces of equipment such as a machine tool, observing it in actual field use [10].

Failure rate is an important function in reliability analysis since it represents the changes in the probability of failure over the lifetime of equipment or component or even cutting or forming tool. Failure rate at any given time is the proportion of items that will fail in the next unit of time, out of those units that have survived up to that time.

The failure rate can increase, decrease or remain constant over time depending on the equipment's nature. Failure rate can be evaluated from the knowledge of reliability of the life (or reliability) distribution. How the failure rate changes over time gives an insight into the failure mechanisms of equipment and is used in studies for improving reliability. The failure rate curve that seems applicable to a wide variety of complex equipment is shown in Figure 2, known as bathtub curve due to its peculiar shape. Such a curve divides the life of equipment into three distinct regions, [7].

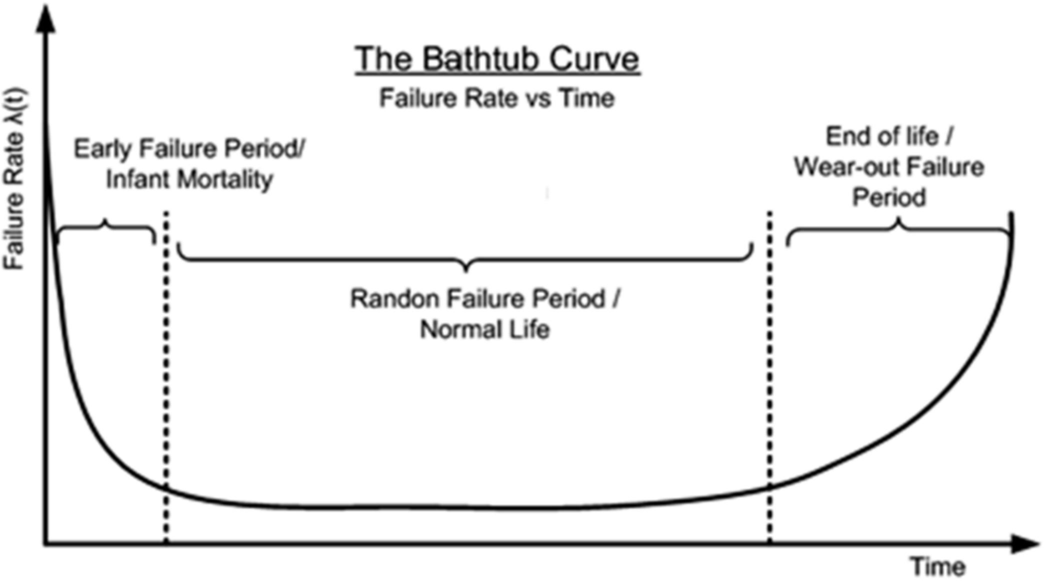


Figure 2. Failure Rate Curve – Bathtub Curve.

The, so-called burn-in early failure region exhibits decreasing failure rate. That decrease is due to defective units in the population, caused by poor material or failures in manufacturing processes, failing early and being repaired or removed from the population. The chance failure region presents an almost constant failure rate. Here, failures occur not because of inherent defects in the units but because of accidental occurrence of loads in excess of the design strength [9].

The constant failure rate approximation is often quite adequate even though a system or some of its components may exhibit moderate early-failures or aging effects. The magnitude of early failures is limited by strictly quality control in manufacturing and aging effects can be sharply limited by careful predictive or preventive maintenance.

Finally, the wear-out region is characterized by a complex aging phenomena, representing an increasing failure rate. Failures occur due to the development of cumulative damage mechanism such as wear, corrosion or fatigue. Knowledge of when wear-out begins helps in planning replacements and overhauls.

The failure rate λ(t) at any time *t* is expressed according to Eq. (3):

$$\lambda(t) = \frac{f(t)}{R(t)} \tag{3}$$

where *f*(t) is the probability density function associated with reliability distribution

The reliability of each equipment subsystem is calculated based on the failure data and the equipment reliability is simulated through the use of a block diagram. Reliability block diagram is frequently used to model, in a quantitatively way, the effect of item failures on system performance. It corresponds to the information flow arrangement among the items in the system. A block represents one or a collection of some basic parts of the system for which reliability data are available, [8].

Basically, there are two basic configurations of block diagrams: series or parallel systems. In a series system, the components are connected in such a manner that if one of the components fail the entire system fails, as shown in Figure 3a. In a parallel system, named as active redundancy, the system fails only when all of the components fail, as shown in Figure 3b. For that configuration, the redundant component is always alive. In this configuration, the system will perform its function if at least one of the components is working. In parallel standby systems, the redundant component is activated only after the main component has failed [9].

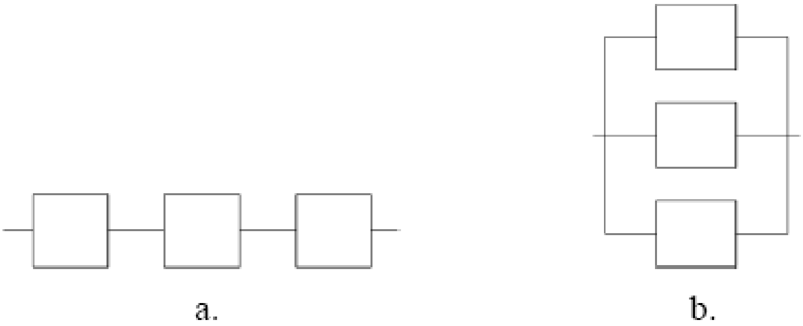


Figure 3. Reliability Block Diagram basic configurations. a) Series system b) Parallel system.

For a series system, considering that the component failures are independent probabilistic events, the system reliability in any time t is given as the product of component reliability and expressed according to Eq. (4):

$$R_s(t) = R_1(t).R_2(t)...R_k(t) \tag{4}$$

where R_s(t) is system reliability at time *t*, R_i(t) is ith component reliability at time *t*.

Table 2. Example of Process FMEA Worksheet Format

PROCESS FAILURE MODE AND EFFECTS ANALYSIS

PART NUMBER______________ DATE________
REFERENCE DRAWING_______ SHEET___OF__

PROCESS FUNCTION/ REQUIREMENTS	POTENTIAL FAILURE MODE	POTENTIAL EFFECTS OF FAILURE	POTENTIAL CAUSES/ MECHANISM OF FAILURE	PROCESS CONTROL	SEVERITY	OCCURRENCE	DETECTION	RPN

Adapted from [9].

For an active parallel system, also considering the component failures as independent events, the system reliability is expressed according to Eq. (5):

$$R_s(t)=1-[1-R_1(t)].[1-R2(t)]..[1-R_k(t)] \tag{5}$$

Complex pieces of equipment can be represented as a combination of series and parallel systems. The system must be modeled through a reliability block diagram and the reliability computed by evaluating reliability of subsystems in a bottom-up manner.

As a complement for the reliability numerical analysis, the manufacturing planner can develop a qualitative method to define the possible relations between the machine tool, tools, jigs and fixture failures failure modes and their effects on the manufacturing process, mainly on the product quality, the process reliability and human and environmental safety.

That analysis is performed based on the failure modes and affects analysis (FMEA) concepts and is commonly named Process FMEA (PFMEA). The PFMEA analysis can be developed according to the following steps:

i) For each process element (tool, machine tool, jigs and fixtures), determine the possible potential failure modes such as wear, lack of lubrication, incorrect assembly and others, where the occurrence can affect the performance of the manufacturing process.
ii) Describe the effects of those failure modes. For each failure mode identified, the PFMEA development team should determine what the ultimate effect will be on the manufacturing process. Examples of failure effects include: injury to the machine operators; inoperability of the machine tool affecting production planning; loss of precision in the part manufacturing (loss of part quality) and others.
iii) Identify the causes for each failure mode. A failure cause is defined as a design weakness that may result in a failure. The potential causes for each failure mode should be identified and documented.
iv) Enter the Probability factor. A numerical weight should be assigned to each cause that indicates how likely that cause is (probability of the cause occurrence). A common industry standard scale uses 1 to represent not likely and 10 to indicate inevitable.
v) Identify Current Controls (design or process). These are the mechanisms that prevent the cause of the failure mode from occurring or which detects the failure before it reaches the Customer. The team should identify testing, analysis, monitoring, and other techniques that can or have been used on the same or similar processes to detect failures. Each of these controls should be assessed to determine how well it is expected to identify or detect failure modes.
vi) Determine the likelihood of Detection. Detection is an assessment of the likelihood that the Current Process Controls will detect the Cause of the Failure Mode or the Failure Mode itself.
vii) Estimate Risk Priority Numbers (RPN). The Risk Priority Number is a mathematical product of the numerical Severity, Probability, and Detection ratings:
RPN = (Severity) x (Probability) x (Detection)

The RPN is used to prioritize items than require additional quality planning and maintenance requirements review.

viii) Determine Recommended Action(s) to address potential failures that have a high RPN. These actions could include specific inspection, testing or quality procedures; selection of different machines tools or tools; de-rating; limiting environmental stresses or operating range; monitoring mechanisms and performing preventative maintenance.

The FMEA analysis is executed with the use of a table such as the one presented in Table 2.

4. RELIABILITY FACTORS IN MACHINING MANUFACTURING PROCESS

This section of the chapter discusses the application of reliability concepts to model manufacturing process reliability.

Although those concepts can be applied to any manufacturing process, the main focus of this item is the machining process. The machine process is the most used manufacturing process in the mechanical industry, once parts that are manufactured by forming or casting usually are machined in order to control dimensional and geometrical tolerances and surface finishing.

Usually, the reliability of a manufacturing operation depends on three independent factors: operator, machine-tool and cutting tool. The reliability of each factor may be modeled by means of statistical distribution.

The following sections present some discussions regarding the failure modes and reliability models that can be used to define the machining process reliability.

4.1. Operator

People are affected by their environments in many ways. For example, social environment, heat or cold, light conditions and time pressure all have the potential of influencing human performance. One measure of the quality of work performance is the number of errors made by the people at work. Errors that are caused by human operators are referred to as 'human errors' [11].

Failure (or error) in this sense is usually defined as the failure to perform an act within the limits (of time or accuracy) required for safe system performance or the performance of a non -required act which interferes with system performance. The errors are classified as random and systematic errors.

Systematic errors are biases which lead to the situation where the mean of many separate measurements differs significantly from the actual value. Sources of systematic errors may be imperfect calibration of measurement instruments or incorrect use of the instrument by the operator. Systematic errors are detected applying statistical methods to the monitoring and control of a process and are corrected with frequent calibration of instruments and operator training.

Random errors are caused by unknown and unpredictable changes in the process. These changes may occur in the tools, in the environmental conditions or in complex man-machine interfaces. The random human errors introduce the possibility of manufacturing non-conforming parts, and this may become a function of physical or emotional fatigue of the operator. The effect of the random errors may be reduced by operator training or observation and averaging the outcomes. Furthermore, through the application of time and motion studies that consider the pauses at work and the division, workflows can be analyzed and synthesized with the objective of improving labor productivity.

The operator reliability may be defined experimentally based on the register of the number of errors that occurred during a specific period of observation.

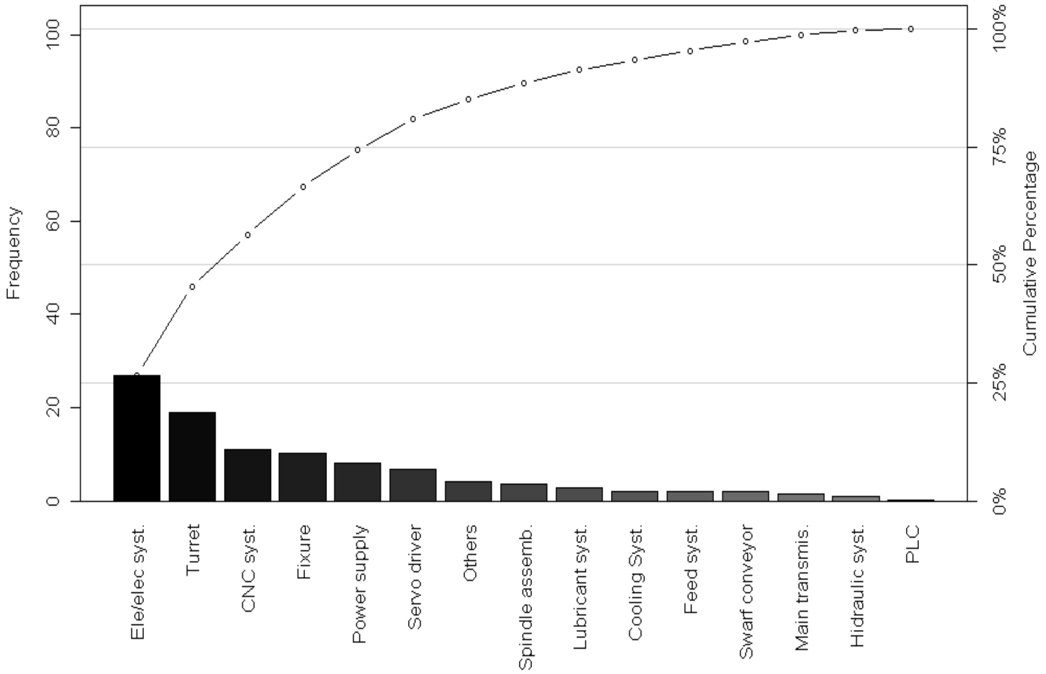
4.2. Machine

The machine reliability depends on the machine architecture and design characteristics, including the degree of automation, the operational environment and also on the maintenance policy. However, as the breakdown of a single machine may result in the production of an entire workshop being halted and repairs may be more difficult and expensive when a breakdown occurs, the availability of the production line can be severely impacted by an unexpected machine failure. Wang et al. [12] show the main subsystems in a machine tool that present great frequency of failures which are the electric and electronic system, turret, CNC system, chuck and clamping fixture, power supply, servo unit. The most critical mechanical subsystems as for failure and reliability analysis are the turret and chuck (Figure 4).

Usually the reliability of each subsystem is different once it is dependent on the nature of the subsystem, such as mechanical or electrical/electronic. There are some subsystems with random failure such as the sensors and servo unit, while other subsystems present failures associated with damage accumulation processes for instance shaft, gear box, and bearings.

Researches were developed aimed at analyzing machine reliability used in mechanical parts manufacturing. Wang et al. [12] present a study about the failure modes and causes and define the weakest subsystems subsystem on CNC machines based on a probabilistic model developed through the study of failures in 80 CNC lathes, collected over a period of two years. This study established that the failure could be best described using the Lognormal distribution with mean 5.1758 and standard deviation 1.1370, the variable’s natural logarithm, as shown in Figure 5.

Beginning-of-life equipment can present random failure (failure mode typical of electrical and electronic components), but after 100 hours of use without maintenance, the hazard failure is increased, as show in Figure 5, indicating the beginning aging stage where phenomena such as fatigue and wear of mechanical components are predominant which affects the machine performance.



Adapted from [12].

Figure 4. Pareto chart of failure for CNC lathe.

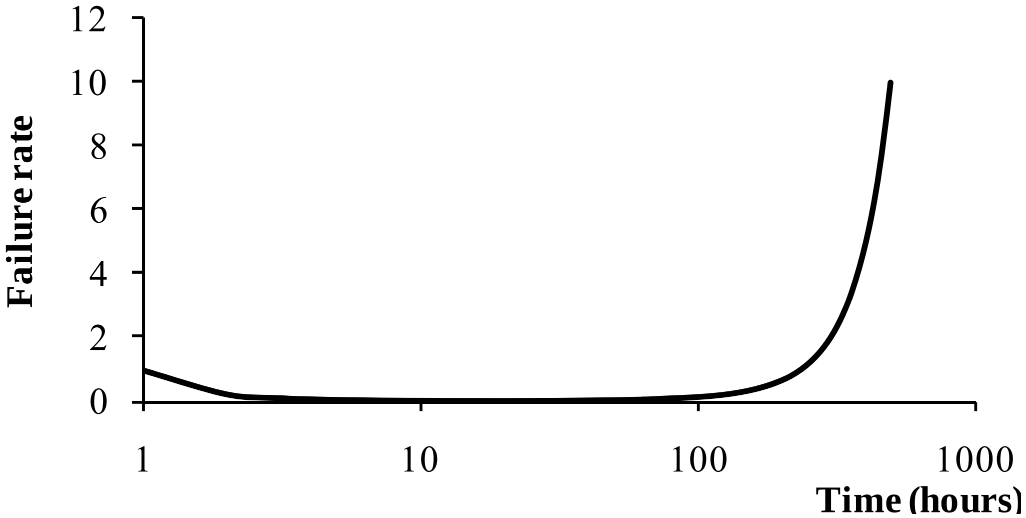


Figure 5. Failure rate for electromechanical machines – Lognormal Distribution (5.1758 , 1.1370).

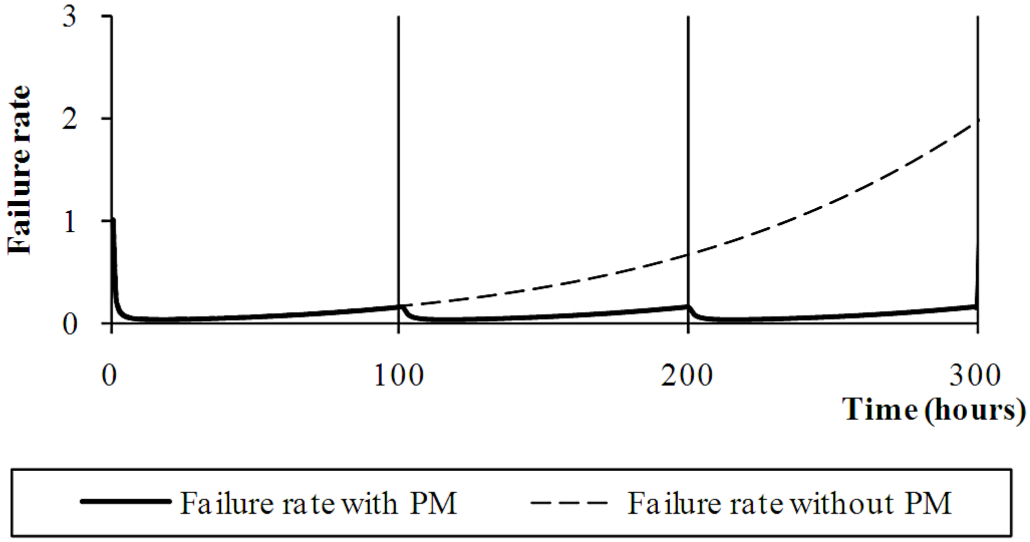


Figure 6. Behavior of failure rate with preventive maintenance. Intervention Interval: 100 hours [15].

The result of Wang et al. [12] conflict with other authors such as Mejabi and Black [13] and Freiheit and Hu [14] who established that the probability of failure in a manufacturing equipment can be modeled with the use of an exponential distribution. The exponential distribution would be used considering aspects such as: preventive maintenance, application of Failure Modes and Effect Analysis (FMEA) to improve the design of critical subsystems, and application of design methods based on "design life criterion" for the main mechanical components [15].

Preventive maintenance is a schedule of planned maintenance actions aimed at the prevention of unexpected breakdowns and failures. The primary goal of preventive maintenance is to prevent the failure of equipment before it actually occurs. It is designed to preserve and enhance equipment reliability by replacing worn components before they actually fail. Preventive maintenance activities include equipment checks, partial or complete overhauls at specified periods, oil changes, lubrication and so on. In addition, workers can record equipment deterioration so they can know the time to replace or repair worn parts before they cause system failure. The preventive maintenance program aims at preventing all equipment failure due to aging effects. The machine would ideally present random failures and its reliability can be modeled by an exponential distribution, as shown in Figure 6.

Nevertheless, the machine operational time without preventive maintenance must not exceed the beginning of the increased failure rate associated with the wear of power system components. Furthermore the mechanical main components as shaft and gear assembly are designed with infinite lifetime and high level of reliability. These facts can significantly delay the aging effects. Therefore, under these considerations it is possible to model the lifetime by an exponential distribution. The FMEA is an engineering technique used to define, identify, and eliminate known and/or potential failures, problems, and errors in the machines design enhancing their reliability.

4.3. Tool

During the machining process, the cutting tools are loaded with heavy forces resulting from the deformation process in chip formation and friction between the tool and work piece. The heat generated at the deformation and friction zones overheats the tool, the chip and partially, the work piece. All the contact surfaces are usually clean and chemically very active; therefore the cutting process is connected with complex physical-chemical processes. Tool wear, which occurs as the consequence of such processes, is reflected as progressive wearing of particles from the tool surface.

As for manufacturing process reliability analysis, the definition of cutting tool change time can be based on cutting tool reliability analysis. That analysis aims at keeping the tool reliability greater than a minimum target value that will reduce the chance of non-conforming parts manufacturing. The reliability of the cutting tool represents the probability that the tool wear is lower than a pre-defined value, in a given operational time.

The defects introduced in parts, as a function of tools failure, have increasing failure rate increase in time since the main tool failure mode is wear and the tool wear is accumulative damage mechanism. Therefore, the tool reliability must be represented by a probability distribution function that simulates increasing failure rates with time as the Normal distribution, Weibull distribution and Lognormal distribution. Some authors such as Freiheit and Hu [14], purpose the exponential distribution is appropriate to model the wear tool, which is not suitable to model failures associated with aging effects.

Some works aiming at modeling tool reliability are based on the methodology developed by Hitomi et al. [16], such as those developed by Wang et al. [17], El Wardany and Elbestawi [18], and Patino Rodriguez [15], where a reliability-dependent failure rate model is used to predict the reliability of a cutting tool subject to flank wear with Lognormal distribution.

It is assumed that the distribution of average flank wear (V_B) follows a Lognormal distribution. Whether tool wear fit another distribution, it is possible to follow this procedure and to find the tool reliability in terms of lifetime.

Let V_B be a random variable that represents the tool flank wear. The tool flank wear is a function (Ψ) of the cutting conditions and tool geometry. This function can be given by Eq. (6).

$$v_B = \psi(f, \upsilon, d, t, \gamma, r) \cdot \theta(\xi) \tag{6}$$

where *f*: feed rate (mm/rev), υ: cutting speed (m/min), *d*: depth of cut (mm), *t*: cutting time (min), γ: angle, r: radius, and θ: error.

By taking the logarithms of both sides of the Eq. 10, the following linear relation is obtained Eq. (7).

$$\begin{aligned} \ln(v_B) &= \ln[\psi(f, \upsilon, d, t, \gamma, r) \cdot \theta(\xi)] \\ \ln(v_B) &= \ln[\psi(f, \upsilon, d, t, \gamma, r)] + \ln[\theta(\xi)] \\ \ln(v_B) &= \ln[\psi(f, \upsilon, d, t, \gamma, r)] + \ln[\theta(\xi)] \end{aligned} \tag{7}$$

The median of flank wear (V_{B0}) and the variance (σ^2) represents the dispersion of the values for tool wear, the difference between the Taylor too-life equation value and actual wear value from experimental results. They are calculated from calculated from the relations Eqs. (8) and (9).

$$V_{B_0} = E[\ln(v_B)] = E[\ln(\psi(f,\upsilon,d,t,\gamma,r))] + E[\varepsilon] \tag{8}$$

$$\begin{aligned} Var[ln(v_B)] &= E[(ln(v_B - V_{B0})^2)] \quad \Rightarrow \\ Var[ln(v_B)] &= E[\varepsilon] \quad \Rightarrow \\ Var[\ln(v_B)] &= \sigma^2 \end{aligned} \tag{9}$$

The relationship between tool flank wear V_B and the cutting condition assumed as the Taylor tool-life equations given by Eq. (10).

$$\hat{v}_B = C_0 \cdot f^{b_1} \cdot \upsilon^{b_2} \cdot d^{b_3} \cdot \gamma^{b_4} \cdot r^{b_5} \cdot t^{b_6} \tag{10}$$

where C_0, b_1, b_2, b_3, b_4, b_5, b_6 are constants, which are determined from experimental results and $\hat{v}_B$ is standard wear, value estimated for the cutting conditions.

Assuming that the distribution of average flank wear V_B obeys a Lognormal distribution, the density functions of the flank wear is given by Eq. (11).

$$f(v_B) = \frac{1}{\sqrt{2\pi} \cdot \sigma \cdot v_B} e^{\left[-\frac{1}{2\cdot\sigma^2}(\ln v_B - \ln(C_0 \cdot f^{b1} \cdot \upsilon^{b2} \cdot d^{b3} \cdot \gamma^{b4} \cdot r^{b5} \cdot t^{b6})^2)\right]} \tag{11}$$

Suppose that a cutting tool begins to function at the time period of t=0, and that its failure occurs at t=T. Therefore, the probability that the tool fail at t, F(t), and tool reliability, R(t) are represented by Eqs. (12) and (13).

$$F(T) = P(t \le T) = \int_0^T f(t)dt \tag{12}$$

$$\begin{aligned} R(T) &= 1 - F(T) \quad \Rightarrow \\ R(T) &= 1 - \int_0^T f(t)dt \end{aligned} \tag{13}$$

On the other hand, the probability that the tool life attain to end because the tool wear reached wear limit (V^*_B), is established by Eq. (14).

$$P(v_B \ge V_B^*) = 1 - \int_0^{v_B^8} f(v_B) \cdot dv_B \tag{14}$$

Hence, there is a probabilistic relationship between the time period in that the failure occurs and wear limit (V^*_B), where the end of tool life is judged by the limit of tool wear, as observed in Figure 7.

Figure 7 shows that there is a probability distribution for the observed tool wear at time t, and there is also a probability distribution for the time that the tool reached its wear limit (V^*_B). By observing the tool wear evolution, it is possible to verify that for each moment of time, there is a likelihood of tool wear being less than V^*_B. This probability is reduced when the tool usage time is increased. Beside, the time where $t = \hat{T}_1$ is defined as the mean time which the tool wear reaches limit value V^*_B. The estimated for $\hat{T}_1$ is showed in Eq. (15).

$$
\begin{aligned}
&P(T < t) = P\left(v_B \geq V_B^*\right) \\
&\int_0^t f(t)\cdot dt = 1 - \int_0^{v_V^*} f\left(v_B\right)\cdot dv_B
\end{aligned}
\tag{15}
$$

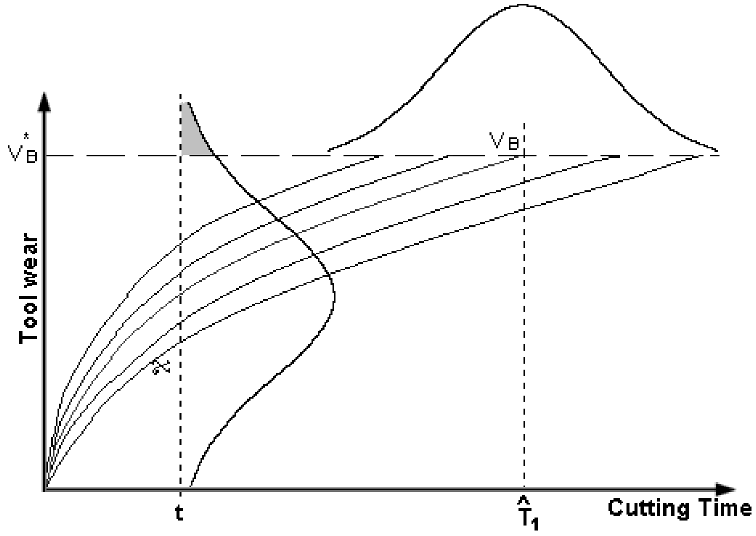


Figure 7. Relationship between time t and tool wear V_B [15].

Using the above conclusions, the tool reliability at time T=t as a wear function is presented in Eq. (16).

$$
\begin{aligned}
&R(t) = 1 - P(T < t) \\
&R(t) = \int_t^{\infty} \frac{1}{\sqrt{2\pi}\cdot\left(\sigma/b_6\right)\cdot t}\cdot e^{-\left[\frac{\ln(t)-\ln(T_1)}{\sqrt{2\left(\sigma/b_6\right)}}\right]^2} dt
\end{aligned}
\tag{16}
$$

Substituting $t = \hat{T}_1$ into Eq. (10):

$$\hat{T}_1 = \left[\frac{V_B^*}{C_0 \cdot s^{b_1} \cdot \upsilon^{b_2} \cdot d^{b_3} \cdot \gamma^{b_4} \cdot r^{b_5}} \right]^{1/b_6} \tag{17}$$

Thus, the tool-life distribution, which is determined from the tool-wear distribution, also obeys the Lognormal distribution as shown in Eq. (18).

$$f(t) = \frac{1}{\sqrt{2\pi} \cdot \hat{\sigma} \cdot t} e^{\left[-\frac{1}{2 \cdot \hat{\sigma}^2} (\ln \hat{T}_1 - \ln\left(t\right)^2 \right)\right]}$$

$$F(t) = \Phi\left(\frac{ln\,\hat{T}_1 - ln\,t}{\hat{\sigma}} \right) \tag{18}$$

4.4. Applications of Tool Reliability Analysis

Turning Process

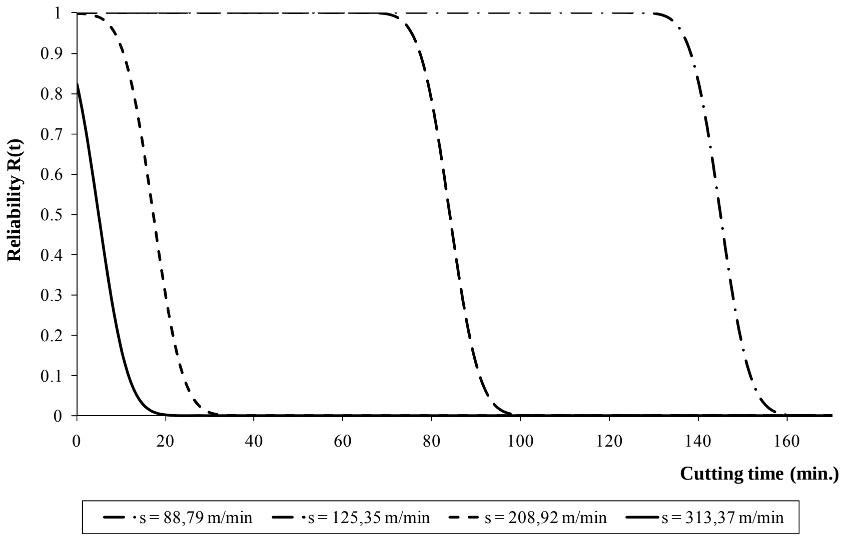
First, the experimental data reported by Hitomi et al. [16] employing carbon steel as the cutting tool material are presented. The work piece length was 500 mm, with a diameter of 100 mm. The work piece was clamped in a high-speed lathe and a throwaway- type carbide insert tip was used to perform dry cutting. The cutting conditions are presented in Table 3. Hitomi et al. [16] compared the characteristics of reliability derived theoretically from the tool life and those obtained experimentally form the tool wear distribution. The tool reliability is kept close to maximum reliability up to 25 minutes to wear limit of 0.3 mm and 32 to wear limit of 0.4 mm, after this time,the tool reliability decreases rapidly.

Table 3. Cutting conditions Hitomi's experiment [16]

Cutting speed (m/min)	Feedrate (mm/rev)	Depth of cut (mm)	Limit value of flank wear mm
175	0.2	1.5	0.3
175	0.2	1.5	0.4

Table 4. Cutting conditions Wang's experiment [17]

	Cutting speed (m/min)			
	88.1979	125.35	208.92	313.37
Feedrate (mm/rev)	0.2	0.2	0.2	0.2
Depth of cut (mm)	1.5	1.5	1.5	1.5
Time mean tool life, T_1, (min)	245.11	84.07	17.23	4.90
Variance σ^2	3,3954	3,3395	0,3490	0,3104



Adapted from Wang et al. [16].

Figure 8. Turning cutting tool reliability.

Wang et al. [17] developed experiments using high carbon steel as the experimental material, and a number of tool wear experiments were carried out on a heavy duty lathe employing a sintered carbide insert to perform dry cutting. The work piece length was 350 mm with a diameter of 66.5 mm. The mean time for life tool considering the limit value of flank wear as 0,3 mm was determined. The tools were tested 4 cutting speed. The experimental conditions are presented in Table 4.

Based on the theoretical development shown in section 4.3 and using the Eq. (17), the time mean tool life for each cutting speed, as shown in Table 4 was found. Figure 8 shows the reliability behavior in terms of the cutting speed, following a Lognormal distribution with mean $\hat{T}_1$ .and variance.

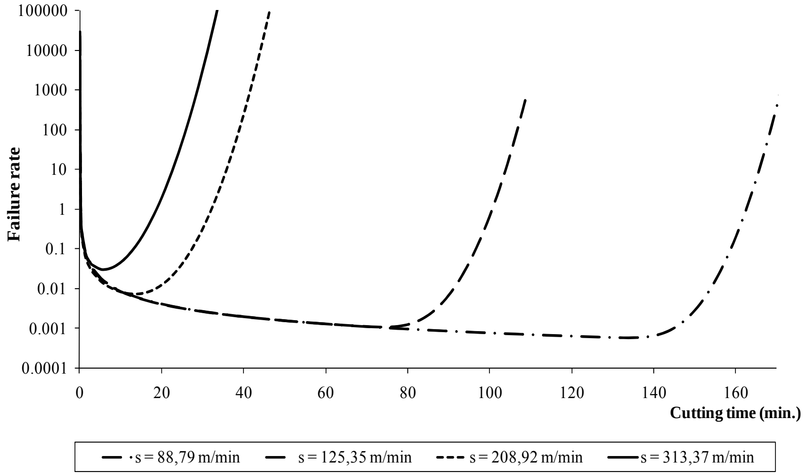


Figure 9. Failure rate of turning cutting tool.

Table 5. Cutting conditions Patino Rodriguez's experiment [15]

Diameter (mm)	5
Depth of cut (mm)	25
Feedrate (mm/rev)	0.025
Rotation (rpm)	4000
Cutting seep (mm/min)	62831

Using Wang et al.´s experimental data, the failure rate for was calculated applying Eq. (3) and presented in Figure 9. The failure rate increases for all cutting conditions. When cutting speed is low, the early failure period increases. This behavior can be explained due to the fact that when the cutting speed is slow the wear rate is lower. The tool premature failures under these conditions are due to problems with tool manufacturing process or tool material.

Drilling Process

Patino Rodriguez [15] defined experimentally the drilling tool reliability through the execution of controlled drilling test. A M2 HSS drill was used to drill holes in an ASTM 1010 steel block. During the experiments the machining feed rate and speed were controlled. The cutting conditions are presented in Table 5.

After the execution of a group of five holes, the drill flank wear was evaluated based on images captured using a microscope. The holes are drilled until the flank wear is greater than 0.120 mm, defined as the maximum allowable drill wear. That experiment was executed with 10 drills. Based on the distribution of number drilled holes until the flank wear is 0.120 mm, the cutting tool reliability is defined.

The drilling tool reliability distribution parameters are estimated through the Lognormal distribution with mean 10.08 and variance 0.0599, where the mean and variance from a domain of Normal distributions (See Figure 10).

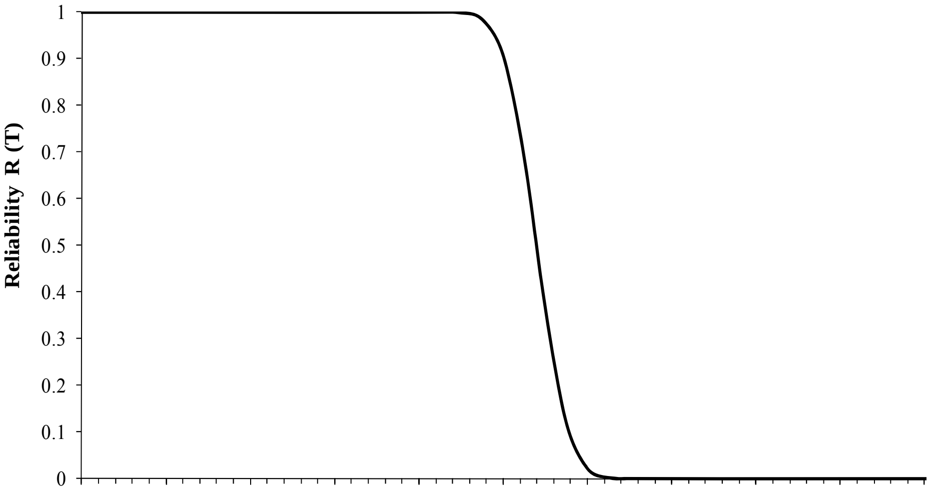


Figure 10. Tool reliability of drilling cutting tool [15].

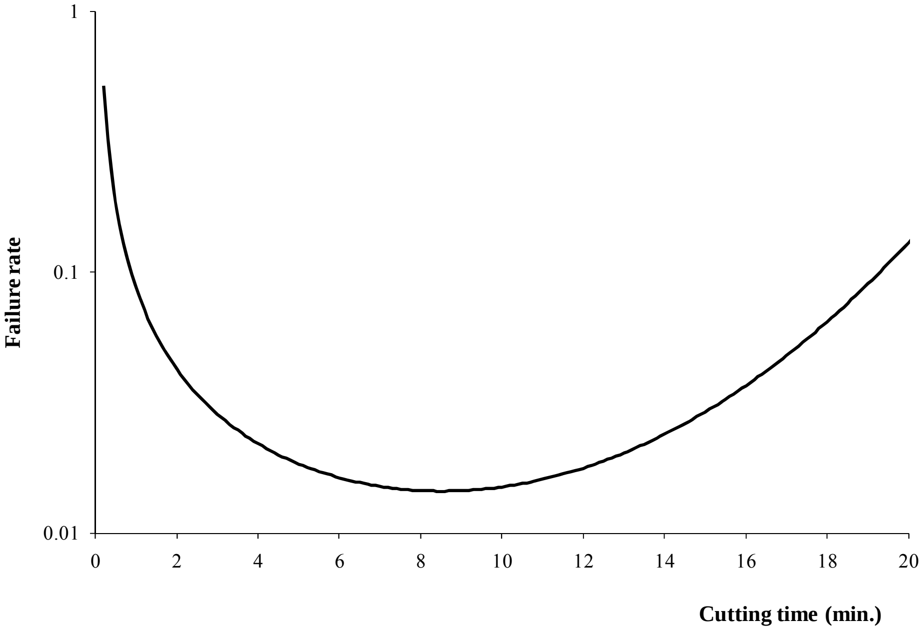


Figure 11. Failure rate of drilling cutting tool.

The drilling tool reliability decreases rapidly when the drilling time over-spends 8.40 minutes. In this case, the flank wear presents great magnitude affecting the quality of the produced holes.

The failure rate for experimental data of Patino Rodriguez [15] was calculated applying the Eq. (3) and is presented in Figure 11.

In both cases presented, it is emphasized that a Lognormal distribution is an appropriate density probability function used to model wear-related phenomena that results in failure rate increases with time, because the time to failure related to cutting tool wear usually presents a large uncertainty [7].

The tool wear has lead to the loss of dimensional and geometrical tolerances of machined parts but the relationship between the tool wear and loss of tolerance manufactured part is not yet well-defined.

4.5. Calculating Reliability of a Part Manufacturing Process

A manufacturing process is defined as a sequence of pre-established operations, aimed at producing a specific part or product. The reliability of the process may be evaluated using reliability concepts such as block diagram and probability distribution function to describe the likelihood of failures for both machines and tools. Usually, the reliability of an operation depends on three independent factors: operator, machine-tool and cutting tool. The process reliability depends on the operation sequence and their reliability. The operation reliability is a statistical relation between cutting tool, operator and machine-tool reliability.

The reliability of a part manufacturing process is mainly determined by the cutting time for each job and by the sequence of operations, defined by the series configuration. The reliability of a given job in any manufacturing process is calculated according to Eq. (20):

$$R_{operation}(t) = R_{operator}(t) \cdot R_{machine}(t) \cdot R_{tool}(t) \qquad (20)$$

where, $R_{operation}(t)$ is the reliability of the manufacturing operation at a given time t, $R_{machine}$(t) is the reliability of the machine at a given time t, $R_{tool}(t)$ is the reliability of the cutting tool at a given time t, and $R_{operator}$(t) is the reliability of the machine operator at a given time t.

The reliability of the cutting tool may be estimated based on literature review or experimental results as we explain below. The reliability for a specific machine must be experimentally evaluated based on 'time to failure' database, as shown in 1.3 .4 the machine-tool reliability is modeled according to an exponential distribution, which the parameter is dependent on the electrical motor, spindle and bearings failure rates. The operator reliability is also defined experimentally based on the register of the number of errors that occurred during a specific period of observation.

The failure rate for a manufacturing process begins with a decreasing failure rate, named as the early failure period (also referred to as infant mortality period). Failures during infant mortality are highly undesirable and are always caused by defects and blunders: material defects, design blunders, errors in assembly or errors in tool selection. Appropriate specifications and adequate design tolerance can help, and should always be used, but even the best design intent can fail to cover all possible interactions of components in operation. In addition to the best design approaches, stress testing should be started at the earliest development phases and used to evaluate design weaknesses and uncover specific assembly and materials problems. These errors cause the production of defective parts early in the process attracting the attention of the operator and quality inspectors that there is a problem with any process or machine. This decreasing failure rate typically lasts several weeks to a few months.

Next, a useful life period is expected, where the failure rate function is constant over time. This period of constant failure rate is known as the random failure period. Useful life failures are normally considered to be random cases of "stress exceeding strength", whether the part design and processes are well designed. The failures are usually due to forces external to the product, such as mishandling, external interface failures, or accidents. However, many failures often considered normal life failures are actually infant mortality failures. The constant failure rate is used for quality control to predict the total of defective parts in a batch, and sometime in probabilistic judgments, which are based on binomial, Poisson or exponential distribution.

Concluding with a wear-out period that exhibits an increasing failure rate, which begins to increase as tool materials wear out and machines degradation failures occur at an ever increasing rate.

The analysis presented here shows that machines scheduling and tool change are essential to guarantee the reliability of a specific part manufacturing process, so tool change time is a function of the tool reliability, and the tool reliability is calculated based on tool wear. The cutting tool reliability is critical for any manufacturing process once the time to failure of the cutting tool is extremely lower than the time to failure of machines and operators, thus planning the manufacturing process based on reliability analysis allowed to optimize machining processes with respect aiming at improving product quality, reducing machine down time and lowering production cost.

4.6. Manufacturing Process Reliability Analysis and Tool Change Time Based on Reliability

A process plan generally consists of two parts. A two-layer hierarchy is considered suitable to separate the generic data from those machining-specific. The fist level focuses on part data, analysis machining feature decomposition, machining process selection, grouping of processes into jobs and decisionmaking on heat treatment. The second level considers the detailed working steps for each machining operations, including machine, cutting-tool and fixture selection, cutting-parameter assignment, machining operations sequencing and operations standard time.

The reliability of the manufacturing process is based on process planning knowledge and specifically on sequencing the operations.

Accetturi [20] proposes a model to optimize the selection of operational references, machining methods, machine, cutting-tool and fixture selection and the arrangement of machining operations sequence. Although the proposal is broader, it is only used to select the machine, cutting-tool and fixture, because the aim of this work is static process planning and the reliability is not considered as a constraints factor in the sequencing of the operations.

Accetturi [20] selects machine tools, tooling and fixtures for each machining operation. According to the proposed model, the system's adaptation to a new manufacturing cell is achieved by building a new knowledge base with rules corresponding to the current machining strategy, containing information on the updated machines, tools and fixtures. The factors that have influence on the choice of a manufacturing process are: quantity, complexity of form, nature of material, size of part, section thickness, dimensional accuracy, cost of raw material, possibility of defects and scrap rate. This step is an input for sequencing the operations.

To realize the sequencing the operations, the present authors propose to apply algorithms to obtain a sequencing of operations as a function of priorities imposed by technical, economical and geometrical constraints. Halevi [3] defines these different types of constraints. Required inputs to this phase include a description of the processes as well as machines-tools and tools needed to produce the different features with the precision and surface finish required. These inputs are analyzed and evaluated in order to select an appropriate sequence of processing operations based upon reliability concepts. This step is to define a systematic method to select a suitable process plan based on reliability concepts. The input of this step is the information about the machining features.

A task of the process planning is to select suitable machining sequences for the machined features of the parts to be machined. This process is carried out for each feature, and the following procedure is recommended:

1. To obtain of technical, economical and geometrical constrains
2. To define precedence relationships or anteriorities
3. To select the suitable machining sequence of the machined features.

The sequencing of operations can be modeled as a set of jobs in a series configuration. From the point of view of reliability analysis, the sequence of jobs can be analyzed by a series diagram block as shown Figure 12.

Hence, the sequencing of job plan processes allow the determination of the operating time of each tool and each machine to manufacture a part, and determine the job reliability as indicated in Eq. (20). Knowing the operation reliability, it is possible to establish the manufacturing process reliability as shown in Eq. (21).

$$R_{process}(t) = \prod_{i=1}^{n} R_{operation_i}(t_i) \tag{21}$$

where $t = \sum_{i=1}^{n} t_i$, and t_i is execution time of each job.

Figure 12. Block diagram system for machining operation.

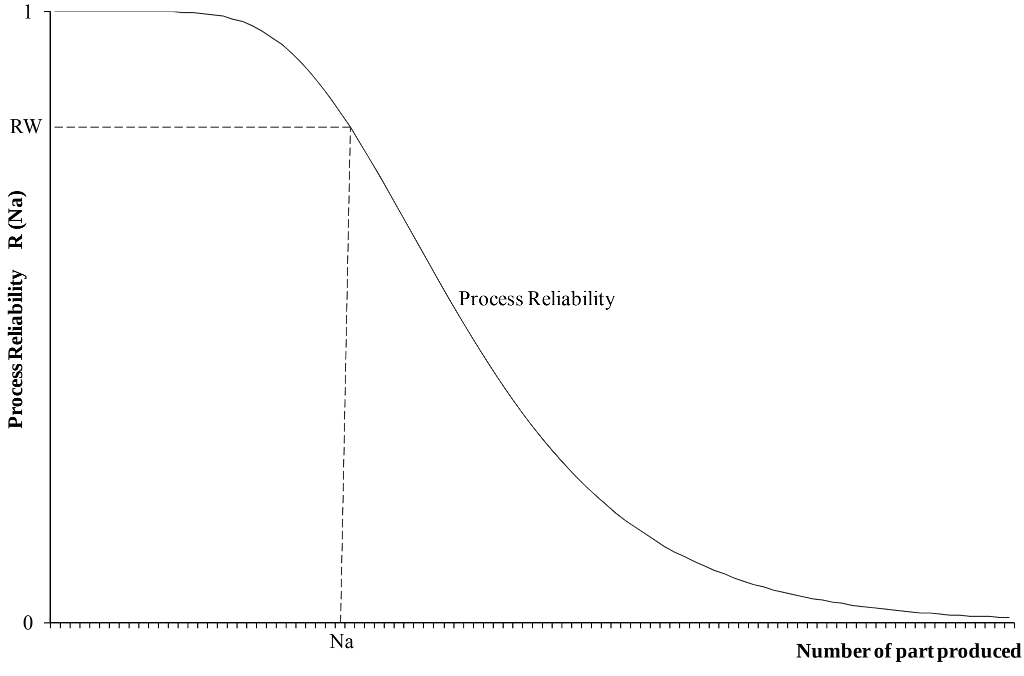


Figure 13. Reliability target in function of number of parts produced.

The operation reliability depends on machine-tool, tool, and operator reliability, nevertheless, the failure tool presents that failure rate increasing and its periodic replacement may alter the manufacturing reliability.

When an active tool wears out, it is replaced by a new one, and the consecutive time interval of tool change varies in terms of the number of parts produced in such an interval (N_a). There is a relationship between time t and N_a as shown in section 4.3. Using this relation and assuming that the reliability for each job is known, it is possible to determine the relationship between N_a and process reliability, as presented in Figure 13. If the cutting tool is not changed after N_a parts are produced, the reliability of the job is reduced, hence the number of non-conforming parts is increased. To avoid this increase it is necessary to define a target reliability required so that the tool wear is not excessive.

Assuming that the time of the job *i* is t_i and that the tool is changed after the production of N_a parts, cutting tool change time (*Tc*) for the job *i* is shown in Eq. (22):

$$Tc = t_i \cdot N_a \tag{22}$$

The problem of tool change time definition becomes more complex when a manufacturing process is analyzed. The manufacturing process is a series system composed of i components (jobs) [15]. In this way, assuming that the time t_i is used for each job, the reliability of the manufacturing process after *N* parts production is calculated as indicated in Eq. (23).

$$R_{process}(t) = \prod_{i=1}^{n} R_i(N \cdot t_i) \tag{23}$$

where $R_{process}(t)$ is the process reliability, R_i is the i^{th} job reliability, *n* is the number of jobs in manufacturing process and *N* is the number of parts produced with the same tool [20].

If the required process reliability is *Rw*, the number of parts that can be produced with the same tool in each of the jobs is Na, as shown in Figure. 13.

Using the reliability of each job and assuming that each one of these operations uses different tools, the critical tool is selected and the change time for each critical tool is determined. If the manufacturing process is composed of only one job and the minimum required process reliability is *Rw*, the number of produced parts (*Na*) is calculated based on the process reliability curve. If the production required is greater than *Na,* the cutting tool must be changed in order to increase the manufacturing process reliability above the minimum value. This procedure is repeated until all parts required by the production planning are produced.

If the manufacturing process is composed of more than one job, the reliability block diagram for the process must be developed. That diagram is a series system composed of jobs.

This chapter considers that during the production period, reduction in both operator and machine-tool reliability are smaller than the reliability reduction caused by tool wear. The algorithm for critical tool selection is described below and is summarized in Figure 14. The use of the information of the priorities of Halevi et al., which aids on machine and tool scheduling problems, and minimizes delays in tool change, is necessary to include the information of change time for each of the tools involved in the process. In the algorithm description, the following notation is used:

T:	Total machining time of one piece $T = \sum t_i$
t_i:	Machining time of i^{th} job
K:	Number of jobs required in manufacturing of one part
N:	Number of required parts
R(t):	Process reliability (calculated)
$R_i(t)$:	i^{th} job reliability
Rw:	Minimum required process reliability (indent left)
H:	Number of tools changes.
Tc (j):	Change time of tool j
$\lambda_i(t)$:	Failure rate of i^{th} tool at time *t*

The reliability of each job is calculated based on Eq. (25) and the procedure presented in Figure 18 is applied.

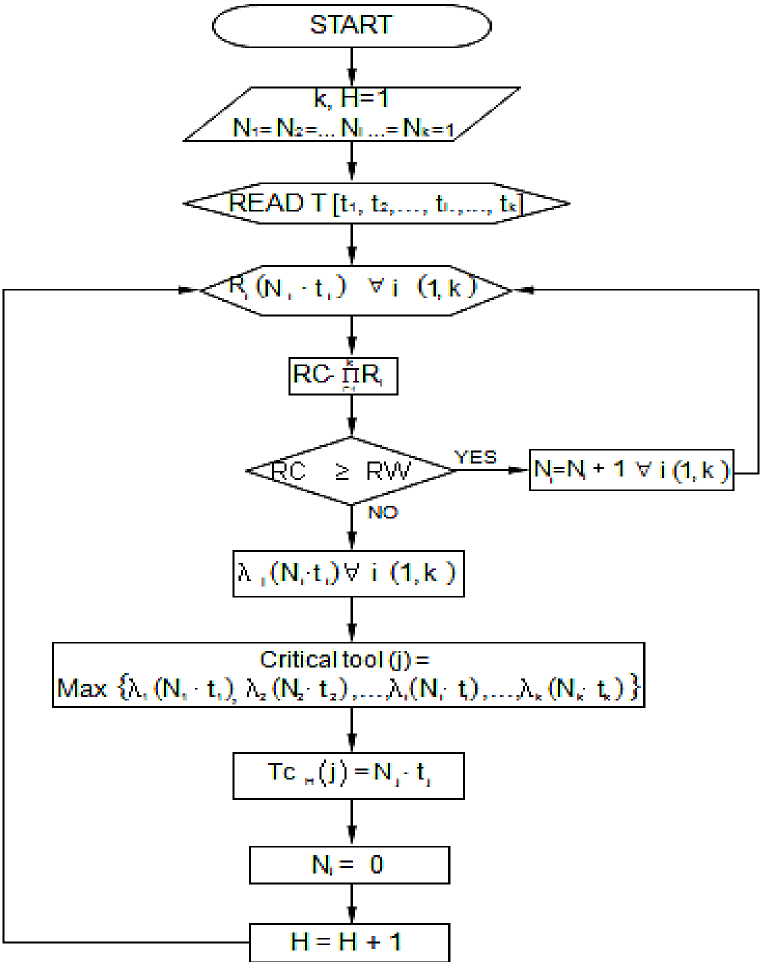


Figure 14. Flowchart illustrating the critical tool selection [19].

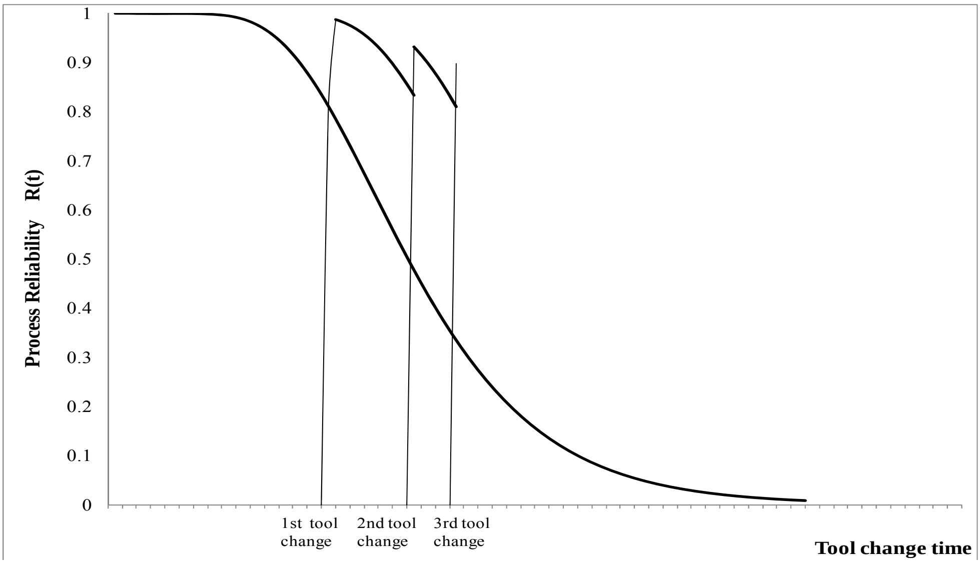


Figure 15. Process Reliability after each tool change.

The procedure basic steps are:

1. The production planner must know the production time for each job, the number of jobs used to produce the part, the total production time for one part and the number of parts to be produced;
2. The planner must calculate the reliability of each job and the process reliability after producing one part;
3. Step 2 must be executed after the production of each part and the counter related to the number of produced parts, the process reliability and the cutting time for the tools used in each job must be continuously updated after the production of one part;
4. The process reliability must be compared with the minimum required reliability at the end of the production of each part. If that reliability is greater than the minimum value, another part can be produced. On the contrary, the manufacturing job with the lowest reliability must be identified and the cutting tool used in the job must be changed. That cutting tool is named as the critical cutting tool;
5. The cutting time for the changed tool is set equal to zero and its reliability is restored to 1. The manufacturing job reliability is increased after tool change. After that change the manufacturing process reliability must be re-calculated;
6. The analysis must return to Step 2. The analysis continues until the number of produced parts achieves the value required by the production planner.

The method to establish tool change time is dynamic since it considers the process reliability based on tool wear for each job. This reliability represents the probability that a given tool reaches the target wear level at a specific time. This target wear level must be selected based on literature information and represents the maximum admitted wear for the tool without affecting the tolerances required for the part being manufactured. The change time of each tool is based on the analysis of the tool hazard rate, guaranteeing that the cutting tool is replaced before it causes a loss of manufacturing parts capability. The algorithm is flexible once it does not pre-define the tool change time. This time is changed during the manufacturing process depending on the condition of the each feature and each tool. After each tool replacement, the process reliability is changed and improved according to Figure 15.

5. APPLICATION

This section presents two applications of manufacturing process planning analysis.

The first example presents the reliability analysis of a precision drilling process, defining as failure, the production of holes with dimensional or geometrical tolerances out of the range defined by the part designers. The reliability analysis is based on the application of Failure Modes and Effects Analysis (FMEA) to analyze the drilling process, in order to define the consequences of machine tool and tool failures, and even drilling conditions out of specification, on the process. The consequences are expressed as a loss of the part tolerances.

The second example discusses the application of the manufacturing process reliability concepts and reliability-based tool change time method in a machining process planning.

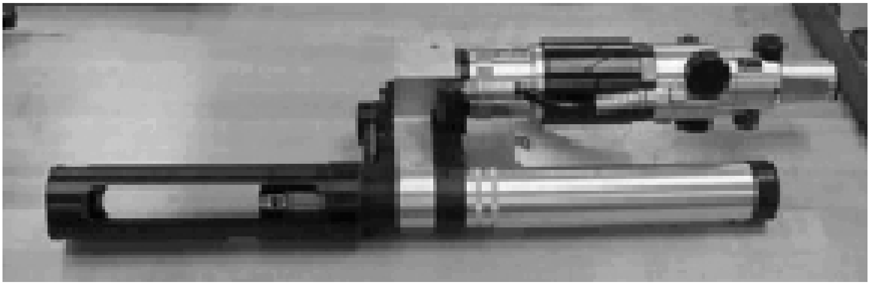


Figure 16. High speed precision drilling machine.

5.1. Precision Manufacturing Process Failure Mode and Effects Analysis

A precision manufacturing process is defined by the dimensional and geometrical tolerances that can be achieved by the manufacturing process. The higher the precision, the greater are the costs associated with the process. Precision manufacturing costs are usually used for mechanical parts that have a great responsibility in providing the structural stability for a given mechanical system. The structural stability is associated with low clearance between parts, absence of surface flaws, or controlled surface roughness. The excessive clearance between structural members can cause wear of fasteners or other joining elements in structures subjected to dynamic loading. Also for dynamic loaded structures, the presence of flaws or excessive surface roughness can increase the fatigue crack growth process.

For aircraft, structural parts that are usually joined with rivets, the hole for rivet installation must be precisely manufactured to provide structural stability. The precision is associated with the dimensional and geometrical tolerances defined for the hole. For aircraft structural parts, the tolerances are very tight and must be designed to be joined with regular size rivets. To achieve the design tolerances, those holes must be manufactured using a precision drilling process.

Taking in view the dimensions and geometry of some aircraft structural parts, the drilling machine must be portable. Furthermore, in order to achieve the high cutting speeds recommended for drilling, some materials employed on those structural parts pneumatic motors power those machines. A typical high speed-drilling machine is shown in Figure 16. Those machines also present a high rotation precision and a device for their coupling to a jig used as a drilling mask.

Table 6. Failure modes and effects analysis for a precision drilling process

a. Precision Drilling Process

Function	Failure Modes	Cause of Failure	Possible Effects	Detection	Criticality
Drill a hole of a pre-defined diameter, with controlled dimensional and geometrical tolerances.	Hole dimensional and form errors.	-Drill wear; -Buckling of the drill; -Drill vibration; -Machine tool spindle run-out; -Inadequate chip removal.	-Reprocessing, in case of dimension smaller than the lower limit; -Use of non-standard rivets, for holes larger than the upper limit.	Dimensional control.	High, for diameters larger than the upper limit.
	Hole perpendicularity errors.	-Incorrect machine tool set up; -Spindle misalignment; -Incorrect drill fixture; -incorrect jig set up.	-assembling problems; -reprocess.	Measurements with a specific metrology procedure.	High
	Hole surface defects.	-Drill wear; -Drill vibration; -Inadequate chip removal.	-Excessive roughness; -Presence of flaws.	Roughness measurement.	Very high
	Hole center position error.	-Incorrect jig manufacturing.	-Assembling problems.	Measurements with a specific metrology procedure	Very high

b. Drill

Function	Failure Modes	Cause of Failure	Possible Effects	Detection	Criticality
Drill a hole of a pre-defined diameter, with controlled dimensional and geometrical tolerances	Wear	-Incorrect cutting speed and feed rate; -Defects in raw material; -Lubrication problems; -Incorrect drill material selection.	-Hole dimensional, location and form errors; -Hole surface defects	-Cutting force or torque monitoring -Flank wear measurement	Very high
	Fracture	-Wear mechanism progression; -Thermal or mechanical fatigue; -Refrigeration and lubrication problems; -Incorrect tool material selection.	-Hole dimensional, location and form errors; -Hole surface defects	Visual inspection	Very high

The aircraft part for which the drilling process is analyzed in this section is located on the plane's main body. The holes are used to install rivets to join two structural sections. The rivets are standard parts and any dimensional or geometrical defect in the holes must be corrected and may induce the use of non-standards rivets to join the structural parts. The aircraft manufacturer must inform the customer about any change in the aircraft components. In future scheduled maintenance actions the maintenance teams must have the non-standard part to be installed in the aircraft. Those changes can increase the aircraft maintenance costs and the complexity of the maintenance planning.

In order to guarantee the correct location of the holes in the part, the manufacturing process employs a special jig, clamped on the part surface with bolts that defines the holes drilling position.

The pneumatic drilling machine uses the holes in the jig as a datum. The chuck's front part of the drilling machine expands, clamping the drilling machine on the jig datum hole's internal surface. This operation guarantees the correct location of the holes and also helps to keep the perpendicularity of the hole regarding the part surface.

Once the drilling machine is installed on the fixture, the drilling process starts. The drilling plan defines the cutting speed and the feed rate that must be adjusted by the operator. The tools are a special step drill that performs the step drilling and the reamer for finishing process, necessary to fulfill the dimensioning and tolerance requirements for each hole. Once the set up is completed, the machine operation is fully automatic.

Considering the drilling process as a system that must be capable of performing a function for a given period of time, the failure mode and effects analysis can be employed for enumerating the possible modes by which the drilling process components, such as drilling machine, drilling tool and even operator, may fail and for tracing through the characteristics and consequences of each mode of failure on the process as a whole.

The failure modes and effects analysis for the precision drilling operation is presented in Table 6.

The criticality associated with each failure mode is related to the consequences of the failure mode on the manufacturing process capability, and consequently, on the hole's dimensional and geometrical characteristics. This attribute is used to separate failure modes that are very critical from those that merely cause inconvenience or moderate economic loss.

As for the precision drilling operation, the surface roughness is a very important control parameter, once the presence of high roughness can increase the probability of fatigue failure of the part. Due to dynamic loading, a crack growth can be foreseen during the aircraft life, which can induce unscheduled maintenance actions, increasing the aircraft operational costs. The maintenance actions involve the crack repair increasing the hole size. Consequently, a non-standard rivet must be used which also increases future maintenance costs.

Any error in the hole center position is very critical for the assembly process. The correct position of the hole center is defined by the drilling jig that can be considered a precision manufactured part. The jig is fully inspected and any imperfection must be corrected before the part is sent to manufacturing plant. Although the jig is considered perfect, any misalignment in the jig mounting can cause problems in the hole center position and even in the perpendicularity of the hole centerline regarding the part surface. So a detailed inspection procedure and special fixture devices must be used when mounting the jig on the part to be drilled.

The hole dimension can be considered critical as for rivet mounting in the assembling line. If the drilled hole is smaller than the lower dimensional limit, a correction action must be taken involving the reprocessing of the hole. This action increases the manufacturing cost but fixes the manufacturing error. Therefore, if the hole dimension is higher than the upper dimensional limit, a non-standard rivet must be used in the assembling line, increasing the future aircraft maintenance costs, due to the use of non-standard parts.

Based on the FMEA analysis results, the process planner must carefully design the manufacturing sequence in order to minimize the probability of occurrence of those defects. The planning tasks involve the drill geometry and material selection, the machine tool selection and the drilling conditions, such as cutting speed and feed rate.

Even using a perfectly designed manufacturing process; the drilled hole presents some dimensional and geometrical variability, which is associated with the process reliability. Manufacturing process reliability can be represented by the bathtub curve presented in Figure 2. The process reliability can be defined as the probability that the dimensional and geometrical characteristics of the manufactured part respect the design tolerance. The manufactured part geometry and dimensions are related to the tool wear [8]. The process life can be modeled as the time to wear a new drill until it fails by excessive wear. The failure rate is related to the probability of drilling holes with dimensions or geometry out of the design's acceptable limits.

In the initial stages, modeled as the first drilled holes, a decreasing failure rate is expected. These infant deaths are related to improper machine tool set-up, use of incorrect drill material or even improper jig mounting. Those failures are easily detected through inspection methods, as those presented on the FMEA table. Once the defects are detected, a corrective action is taken, in order to eliminate the cause of failure. The middle section of the bathtub curve contains the smallest and most nearly constant failure rate. Failures during this period of time are associated with unavoidable overloading in the tool due to deviations in the material mechanical properties, vibrations in the machine tools, machine resolution, repeatability and accuracy, or even random human errors. On the right of the bathtub curve is a region of increasing failure rates. During this period of time, aging failures take place, related to the cumulative wear of the drilling tool, which is the most important cumulative tool failure mechanism. The consequence of the increasing failure rate in a great increase in the production of holes out-of-specification, increasing the need for re-processing, once the tool wear affects the diameter of hole.

The tool wear is a cumulative process that starts with the first use of the tool. In the beginning of the tool life, the wear is small, and the failure rate associated with that failure mechanism is very small in comparison with the early failure rate or even to the random failure rate. The wear grows with the use of the drilling tool and also the probability of drilling holes out-of-specification, increasing the failure rate.

Although the tool wear can be taken as a tool failure indicator, the mechanical manufacturers usually define a tool life based on empirical observations and not on reliability concepts. In order to avoid errors during the manufacturing process, quality control techniques are used to evaluate the manufactured parts. Although the quality control techniques based on control charts and continuous process capability analysis are used to check if the parts are manufactured properly, they are not directly related to the process reliability as discussed in the present chapter.

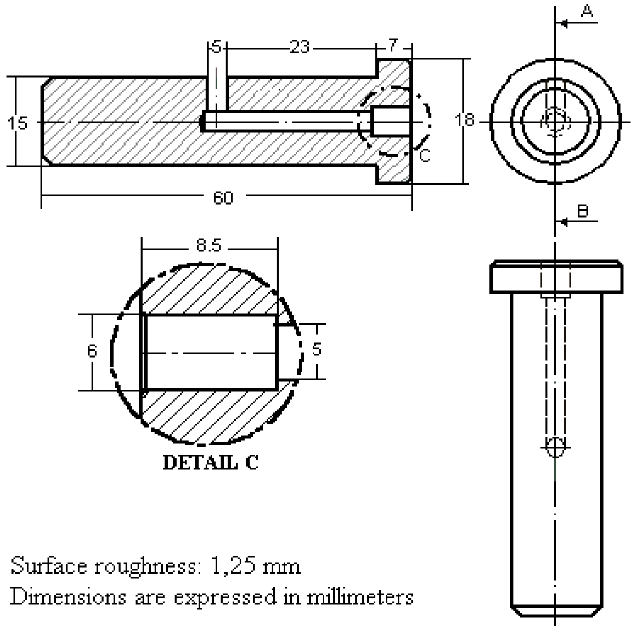


Figure 17. Mechanical drawing of the rotor bearing with lubrication hole.

Table 7. Characteristic for each feature

Group	Machining		Specifications		Cutting conditions [11], [16]			Time [min.]
	Operation	Stage	ϕ [mm]	L [mm]	Feed Rate [mm/rev]	Depth [mm]	Speed [m/min.]	
R_1	Drilling		5	7.5	0.025		62.83	0.0750
R_2	Turning	Rough	18.3	60	0.15	0.5	125.35	0.1835
	Turning	Rough	15.3	53	0.15	0.5	125.35	0.4342
R_3	Turning	½ Finish	18.1	60	0.1	0.1	208.92	0.1633
	Turning	½ Finish	15.1	53	0.1	0.1	208.92	0.1203
R_4	Turning	Finish	18	60	0.08	0.05	313.37	0.1353
	Turning	Finish	15	53	0.08	0.05	313.37	0.0996
R_5	Drilling		6	8.5	0.025	40	62.83	0.1020
	Drilling		5	23	0.025		62.83	0.2300

5.2. Reliability of Manufacturing Process

A case study is used to illustrate the application of the methodology to define tool change time. The case study uses the machining process of a shaft with a lubrication hole used to distribute lubricating fluid to the bearing. The shaft is machining from an SAE/AISI 1010 steel cylinder, with length of 60 mm, and diameter of 18.5 mm (See Figure 17). The specific dimensions, forms, tolerances, and roughness required are obtained using turning and drilling operations.

Table 7 presents dimensions, specifications of machining and the order of precedence and machining times for each operation. Precedence operation is calculated using algorithms and the models presented by Patino Rodriguez [15]. Data presented in this table allows the manufacturing planner to obtain the necessary information about the part.

Reliability calculations are somewhat limited by the available data in the literature and the following hypotheses are used to calculate process reliability.

Consecutive operations are grouped in a same block when the following requirements are fulfilled:

- Machining conditions are identical during operation,
- The machining-grouped operation uses the same tool and,
- The operation of the block is machining in consecutive order (one after the other r).

The tools used for the *finishing*, *½ finishing* and *rough* operations are different, although the machines used in the process (lathes and drilling machine) have an equal hazard rate. In this case, and according to the results presented by Wang [12], the reliability of the machines is modeled using exponential distribution, where the ‘mean time to failure’ is equal to 43603.8 minutes [12]. The mean time between failure of operators involved in the process is much longer than the manufacturing time for the parts, assuming that during the time of part’s manufacture the reliability of the operator is equal to one ($R_{operator}$=1.0).

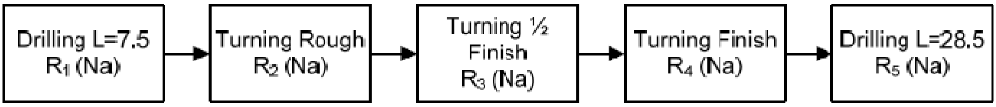


Figure 18. Block Diagram System for machining shaft with lubrication hole.

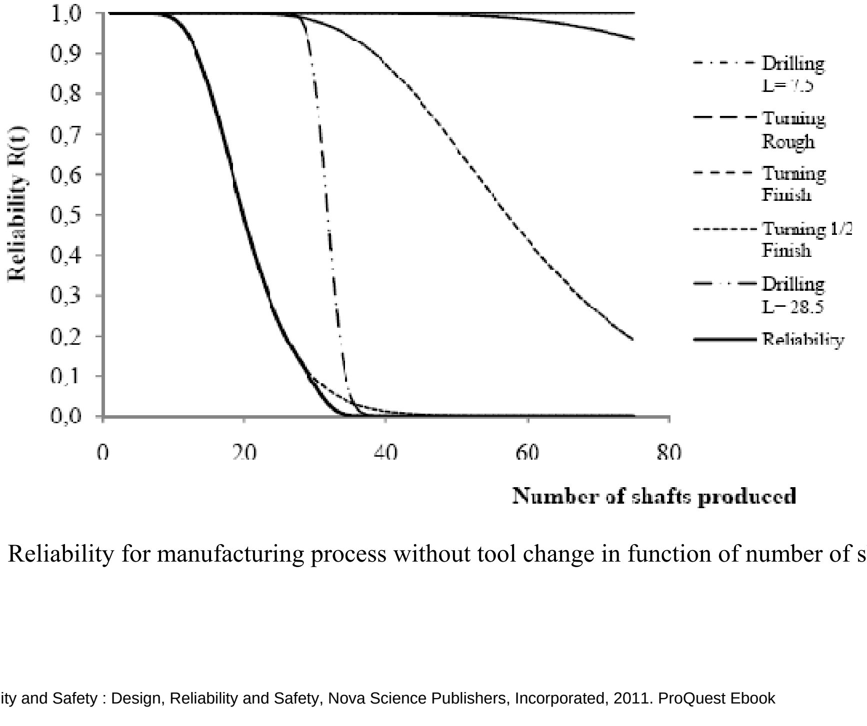


Figure 19. Reliability for manufacturing process without tool change in function of number of shafts produced.

Table 8. Lognormal distribution parameters for cutting tool reliability analysis

Operation	Tool*	T_l	σ^2
Drilling	Drill	10,08	0.0599
Turning Rough	Insert	84.07	0.3395
Turning ½ Finish	Insert	17.23	0.3490
Turning Finish	Insert	4,90	0.3104

Drill: M2 High Speed Steel [16]. Insert: Inserted carbide tip, TNMG160404L2G [11].

Figure 18 shows the block diagram for this case study, according to data presented in Table 7. These blocks represent the part manufacturing operation with a machining time equal to the addition of the machining times for the each operation.

The reliability of the turning and drilling operations is modeled as shown in section 4.4.

Table 8 shown the Lognormal distribution parameter used to model cutting tool reliability where μ and σ^2 are the mean and variance from a domain of normal distributions.

Reliability for the manufacturing process for one part produced is calculated substituting the Eq. 20 in Eq. 21 considering the reliability parameters for machines, tools and operators:

$$R_{process} = \left[\left(1 - \Phi\left(\frac{10.08 - t}{\sqrt{0.0599}}\right)\right) \cdot \left(e^{4360.8^{-1}t}\right) \cdot (1)\right] * \left[\left(1 - \Phi\left(\frac{84.07 - t}{\sqrt{0.3395}}\right)\right) \cdot \left(e^{43603.8^{-1}t}\right) \cdot (1)\right] *$$

$$* \left[\left(1 - \Phi\left(\frac{17.23 - t}{\sqrt{0.3490}}\right)\right) \cdot \left(e^{43603.8^{-1}t}\right) \cdot (1)\right] * \left[\left(1 - \Phi\left(\frac{4.90 - t}{\sqrt{0.3104}}\right)\right) \cdot \left(e^{43603.8^{-1}t}\right) \cdot (1)\right]$$

The time to produce one part, without considering setup time, is 1.562 minutes, and reliability for one shaft manufacturing process is 0,99996. Figure 19 shows the reliability behavior of each manufacturing operation in terms of the number of parts. Turning the ½ finish tool causes the decrease in process reliability for two reasons: this tool has a high hazard rate and it is in use for the longest time. The combination of these two factors implies that this tool has the shortest change time.

This information allows for the calculating of the process reliability and to apply the algorithm presented in Figure 14. Through the increase in the number of manufactured parts, the process reliability is continuously recalculated, once that reliability becomes lower than a given target value, in the present case 80%, a tool must be changed aimed at restoring the process reliability. The tool to be changed is the one with the lowest reliability. The tool change will restore that cutting tool reliability to one.

The process reliability is recalculated and the procedure presented in the preview paragraph is repeated until the reliability is lower than 80% and another tool change is necessary.

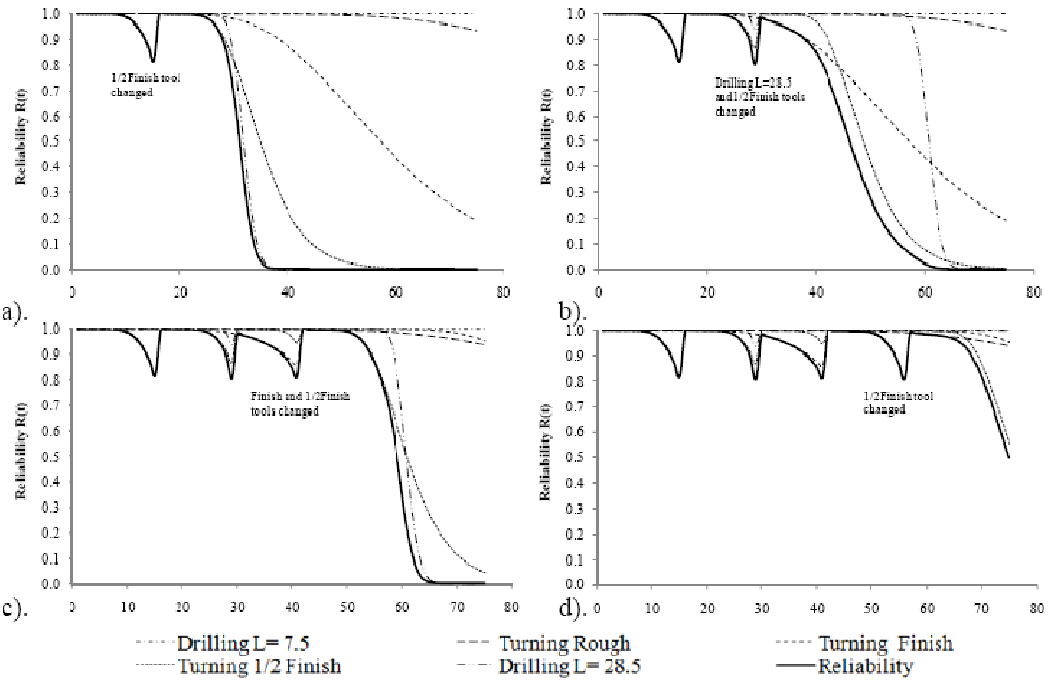


Figure 20. Reliability for manufacturing process with tool change as a function of number of shafts produced. a). 1st tool change. b). 2nd tool change. c) 3rt tool change. 4th tool change.

The value of reliability for the process is reduced until the manufacture of part 16, where the process reliability reached the value of 75.70%, is lower than the required minimum reliability. This value indicates that after of the manufacture of the 15th part, the tool that presents the greatest hazard rate or minor reliability in that instant must be determined. The tool that presents the greatest failure rate, after the manufacturing of 15 parts, is turning the ½ finish tool. Then it is the critical tool and it must be changed. After the tool change, the process reliability is calculated again, and it is observed that the reliability of the manufacturing process for part 16 is 99.94%. Here we can observe the positive effect of this tool change on the process. As the value of the reliability is superior to the required minimum reliability value, this means that the other tools also do not need to be changed, and the process can continue to run until the reliability reaches a value less than 80% (See Figure 20).

The process reliability when manufacturing the shaft, with the changes required to keep the process reliability within the desired reliability limits (0.80 – 1.00) is shown in Figure 20. This figure shows that the number of tools changed, according to the number of shafts produced. It also shows that the tool wear affects the reliability of the manufacturing process.

6. CONCLUSION

The manufacturing process planning is a very important activity in any industrial process. For mechanical industries, the main goal of manufacturing process planning is to define the sequence of operations, machines tools and tools that will be used to manufacture the parts of a given mechanical equipment.

The capacity of the manufacturing process defined experimentally, used to define the chance of manufacturing non-conforming parts. The manufacturing of non-conforming parts is usually caused by failures of the machine-tools or even by non-expected deterioration of the tools. The prediction of the long term performance of machine tools and tools can be based on the reliability concept.

The interaction between machining process parameters, machine reliability and tool reliability has been presented in order to development a method to integrate those concepts to the manufacturing process planning activity. The conditions of the process as defined by the production plan and the machining system influence the process reliability. To the process planner, it is evident that the modeling of the machine and tool reliability can avoid the production of non-conforming parts.

The experiments have shown that Lognormal distribution is the most representative distribution for the tool wear behavior. This model is particularly useful for failure processes which result from many small cumulative factors.

The reliability function for the manufacturing process was derived using tool wear distributions, and machine failure distributions. The calculation of the tool reliability was based on the maximum limit of tool wear and minimum target level for process reliability.

The application process manufacturing reliability avoids that the machining operation reliability decreases that affects the manufacturing process capability, resulting in an increase in the production of non-conforming pieces. The process reliability estimative can be used to define the sequence of tool change and the frequency of that change.

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