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Artículos científicos

Man-Machine System of the Machining Area and the assessment of its reliability

El Sistema hombre-máquina del área de maquinado y la evaluación de su confiabilidad

O sistema homem-máquina da área de usinagem e a avaliação de sua confiabilidade

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Abstract

This paper contains the design of a man-machine system model for the machine tools based on a serial-parallel configuration and their component-subsystem relationships. Causal Analyses and a classification system using the Cluster Analysis were used to analyze the non-conforming pieces that occurred in 3 machine shops from the metal mechanical sector, and to design the man-machine system model. The man-machine system model proposes to provide adequate conditions to apply some statistical reliability assessment models with a serial-parallel systems approach, and on the assumptions of the constant and additive failure rate of the Exponential and Weibull functions respectively. As an input of the first statistical model, the times to failure from non-conforming pieces and goodness of fit test have been used to assess the reliability of component-subsystem relationships. For the second statistical model the reliabilities from component-subsystem relationships were used to assess the reliability of subsystems as serial systems configuration. Inputs for the third statistical model have used reliabilities from subsystems to assess the reliability of the man-machine system as a parallel system configuration. The man-machine system and statistical models were implemented and validated in a company from the metal-mechanical sector with a low-volume and high-mix production rate whose operations were carried out by both conventional and CNC machines.

Based on the man-machine system analysis was possible to know the formal structure of machine tools that generate non-conforming pieces in the scrap area as well as to identify the subcauses of failure that affect the system (components). Components identified were: maintenance/set up, institutional conditions/attitude, admission profile, information/communication, calibration, and supplier. Also, the most common places where failures occurred (subsystems) were identified. Subsystems identified were: machine, tool, process/operation, measurement/instrumentation, programming/design, and material. Through the selected statistical models was possible to get reliability indices for each component-subsystem relationship, for each subsystem as well as for the whole man-machine system, identifying areas for improvement. The company where the methodology was implemented and validated presented a high volume of scrap in the machine tool and it was possible to identify that the subsystem: *process/operation* and the components: *maintenance/set up* and *institutional conditions/attitude* had the lowest reliability, and they were considered as opportunities areas for improvement. For 7 hours the man-machine reliability is 0.1409 (the probability to find a product without failures for which it must be scrapped is 14.09%). In the machine shop, the issues that caused these low levels of reliability are attributed to the insufficient preventive and predictive maintenance program. Improvement actions are considered in another research. This kind of research investigates a little-studied problem, as it is about the reliability of the man-machine system in machining tools and investigates from an innovative perspective and preparing the ground for new studies in the metal mechanical sector.

Keywords: man-machine system, reliability assessment, scrap, serial-parallel system, statistical models.

Resumen

Este trabajo contiene el sistema hombre-máquina del área de maquinado, basado en la configuración serie-paralelo y en las relaciones componente-subsistema. Se utilizó el análisis de causas y un sistema de clasificación mediante el Análisis de Conglomerados, para analizar las piezas no conformes ocurridas en 3 talleres de maquinado del sector metalmecánico y diseñar el modelo del sistema hombre-máquina. El propósito del modelo del sistema hombre-máquina es proveer las condiciones adecuadas para aplicar algunos modelos estadísticos para evaluar la confiabilidad, con en el enfoque de los sistemas serie-paralelo y bajo los supuestos de una tasa de falla constante y aditiva de las distribuciones Exponencial y Weibull respectivamente. Como una entrada del primer modelo estadístico se utilizaron los tiempos para las fallas de las piezas no conformes y pruebas de bondad de ajuste, para evaluar la confiabilidad de las relaciones componente-subsistema. Para el segundo modelo estadístico, se utilizaron las confiabilidades de las relaciones componente-subsistema, para evaluar la confiabilidad de los subsistemas, con la configuración de sistemas en serie. Las entradas del tercer modelo estadístico, se utilizaron las confiabilidades de los subsistemas, para evaluar la confiabilidad del sistema hombre-máquina, con la configuración de un sistema en paralelo. El sistema hombre-máquina y los modelos estadísticos fueron implementados y validados en una compañía del sector metalmecánico con una tasa de producción de bajo volumen y alta mezcla, cuyas operaciones son realizadas por máquinas convencionales y de Control Numérico (CNC).

Con el Sistema hombre-máquina fue posible conocer la estructura formal de las áreas de maquinado desde las piezas no conformes del área de scrap e identificar las subcausas de falla que afectan al sistema (componentes). Los componentes identificados fueron: mantenimiento/set up, condiciones institucionales/actitud, perfil de ingreso, información/comunicación, calibración y proveedor. También fueron identificados los lugares más comunes donde ocurrieron las fallas (subsistemas). Los subsistemas identificados fueron: máquina, herramienta, proceso/operación, medición/instrumentación, programación/diseño y material. A través de los modelos estadísticos fue posible obtener los índices de confiabilidad para cada relación componente-subsistema, para cada subsistema, así como para el sistema hombre-máquina, identificando así áreas para la mejora. La compañía donde se implementó y validó la metodología, presentaba un alto índice de scrap en el área de maquinado y fue posible identificar que el subsistema *proceso/operación* y los componentes *mantenimiento/set up* y *condiciones institucionales/actitud* tuvieron la confiabilidad más baja y fueron consideradas como áreas de oportunidad para la mejora. Durante 7 horas la confiabilidad hombre-máquina es de 0,1409 (la probabilidad de encontrar un producto sin fallos para el que debe ser desechado es del 14.09%). En el taller de maquinado, los problemas que causaron estos bajos niveles de confiabilidad se atribuyen al insuficiente programa de mantenimiento preventivo y predictivo. Las acciones para la mejora están consideradas en otra investigación. Este tipo de investigación estudia un problema poco estudiado, como es la confiabilidad del sistema hombre-máquina en áreas de maquinado e investiga desde una perspectiva innovadora, además de preparar el campo para nuevos estudios en el sector metalmecánico.

Palabras clave: sistema hombre-máquina, evaluación de la confiabilidad, scrap, sistema serie-paralelo, modelo estadístico.

Resumo

Este trabalho contém o sistema homem-máquina da área de usinagem, baseado na configuração série-paralelo e nas relações componente-subsistema. A análise de causa e um sistema de classificação através da Análise de Cluster foram utilizados para analisar as peças não conformes que ocorreram em 3 oficinas de usinagem do setor metalmecânico e projetar o modelo do sistema homem-máquina. O objetivo do modelo de sistema homem-máquina é fornecer as condições adequadas para aplicar alguns modelos estatísticos para avaliar a confiabilidade, com a abordagem dos sistemas série-paralelo e sob as hipóteses de uma taxa de falhas constante e aditiva das distribuições exponenciais. e Weibull respectivamente.

Como entrada para o primeiro modelo estatístico, tempos para falhas de peças não conformes e testes de ajuste foram usados para avaliar a confiabilidade das relações componente-subsistema. Para o segundo modelo estatístico, as confiabilidades das relações componente-subsistema foram utilizadas para avaliar a confiabilidade dos subsistemas, com a configuração dos sistemas em série. As entradas do terceiro modelo estatístico, as confiabilidades dos subsistemas, foram utilizadas para avaliar a confiabilidade do sistema homem-máquina, com a configuração de um sistema paralelo. O sistema homem-máquina e os modelos estatísticos foram implementados e validados em uma empresa do setor metal-mecânico de baixo volume e alta taxa de produção de mix, cujas operações são realizadas por máquinas convencionais e de Controle Numérico (CNC).

Com o sistema homem-máquina foi possível conhecer a estrutura formal das áreas de usinagem a partir das peças não conformes da área de sucata e identificar as subcausas de falha que afetam o sistema (componentes). Os componentes identificados foram: manutenção/configuração, condições/atitude institucionais, perfil de entrada, informação/comunicação, calibração e fornecedor. Também foram identificados os locais mais comuns de ocorrência de falhas (subsistemas). Os subsistemas identificados foram: máquina, ferramenta, processo/operação, medição/instrumentação, programação/projeto e material. Através dos modelos estatísticos foi possível obter os índices de confiabilidade para cada relação componente-subsistema, para cada subsistema, bem como para o sistema homem-máquina, identificando assim áreas de melhoria. A empresa onde a metodologia foi implantada e validada apresentou alto índice de refugo na área de usinagem e foi possível identificar que o subsistema processo/operação e os componentes manutenção/configuração e condições institucionais/atitude tiveram a menor confiabilidade e foram considerados como áreas de oportunidade de melhoria. Durante 7 horas a confiabilidade homem-máquina é de 0,1409 (a probabilidade de encontrar um produto sem defeitos pelo qual deve ser descartado é de 14,09%). Na oficina mecânica, os problemas que causaram esses baixos níveis de confiabilidade são atribuídos a um programa de manutenção preventiva e preditivo insuficiente. Ações de melhoria são consideradas em outra investigação. Esse tipo de pesquisa estuda um problema pouco estudado, como a confiabilidade do sistema homem-máquina nas áreas de usinagem, e investiga sob uma perspectiva inovadora, além de preparar o campo para novos estudos no setor metalmecânico.

Palavras-chave: sistema homem-máquina, avaliação de confiabilidade, sucata, sistema série-paralelo, modelo estatístico.

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Introduction

Complex production systems may count thousands of parts and components subjected to multiple physical and functional connections and interdependencies. This level of complexity inhibits the traditional and statistical approach to reliability engineering, failure prediction, and maintenance planning (Accorsi, Sassi, Manzini, Pascarella, and Patella, 2017). The objective of reliability engineering is the prevention of failures (Barnard, 2015). Prabhakar and Dharmaraj (2017) used reliability analysis professionals with the Weibull Parametric Estimation extensively. The parameters of the distribution provide the measure of the effectiveness of a particular reliability program. According to the development of Industry 4.0 an increase in the integration of digital, physical, and human worlds, reliability engineering must evolve for addressing the existing and future challenges about that (Farsi and Zio, 2018). Zhao, Zhang, and Lu (2018) comment that probability distributions of random variables are necessary for an evaluation of reliability. Generally, probability distributions are determined using one or two parameters determined from collected failure time data or as in Piña-Monarrez, 2017, where they are determined directly from the observed (or expected) mean and standard deviation without any observed failure time data. However, because these distributions are not sufficiently flexible to represent the skewness and kurtosis of data, Weibull models are used to describe various types of observed failures of components and phenomena, as well as to determine their reliability and survival analysis (Lai, Murthy, and Xie, 2006).

Smalko and Szpytko (2008) comment that the man can act as both a decision-maker and as an operator. The psychophysical efficiency of man depends on undertaking faultless decisions, as well as, on correcting controls and skillful machine operation. The worker operates motorized equipment, such as a tool or a machine for production. It includes combinations of one or more workers on one or more pieces of equipment. Workers and machines are combined to take advantage of their respective strengths and attributes. Krüger, Lien, and Verl (2009) said: “are different forms of human-machine cooperation in assembly with the available technologies that support the cooperation”. The analysis, design, and evaluation of man-machine systems present an examination of the construction and application of a combined network and production systems model (Johannsen and Rijnsdorp, 1982). The Matrix method is being proposed for qualitative evaluation of the reliability of technical systems on a finite set of structural elements, introducing the criteria for qualitative assessment of the reliability in the form of structural reliability of the system as the probability of the trouble proof state of this system and the significance of the individual elements in ensuring the structural reliability of the system as a general aggregate of conditional probabilities (Kravets, Kravets, and Burov, 2015).

System reliability, especially for serial-parallel systems, has attracted much attention in recent years. Redundancy allocation is a technique to increase the reliability of serial-parallel systems. Supplying redundant components depends on some restrictions such as available budget, weight, space, etc. (Soltani, Sadjadi, and Tolfig, 2014). A series system is one in which all components must function properly for the system to function properly. A parallel system has failed, only when all systems components have failed. The equation to calculate the reliability for a parallel system is an important contribution from Nachlas (2017) and verifying the real data and comparing with the equation that is traditionally used for the parallel system, being the one indicated by Nachlas (2017) which was the one that yielded reliable data. A redundant system is a system that contains extra components in standby (reserve), which start functioning when a component fails. Thus, a redundant system can be defined as "an element that has 100% reliability for a period, making the whole equation 1". Consequently, once the failure has occurred, if the switching is immediate, the reliability will remain at 100% until the next failure of this element (Tavares, 2004).

Analysis of engineering failures is a complex process requiring information from personnel having expertise in many areas. A failure analysis tries to discover what was fundamentally responsible for the failure from the information gathered. This fundamental cause is termed the "root cause" and helps in the determination of the sequence of events that led to the final failure (Bhaumik, 2019). The probabilistic failure analysis is commonly engaged to improve the safety performance of the system using varieties of methods including fault tree analysis, bow-tie analysis, or block diagram analysis. Such mentioned methods in some cases can be applied with consideration of multi-expert judgment which brings high subjectivity, it is inside (Yazdi, 2019). Sidum and Samson (2018) comment that many safety assessments approach, such as the probabilistic risk assessment method, have been widely used, but they have some challenges such as reliance on the failure rate data, which may not be available.

The manufacturing of parts or pieces in a workshop can range from a single piece to a batch, while it also requires a mixture of them. There are countless types, brands, and models of machines in a machining area, which require the operator's experience, ability, and dexterity for proper handling. They may also use computerized programs, in the case of CNC (computerized numerically controlled) equipment. The man-machine system in this kind of workshop is complex and it requires an effective system to assess its reliability, therefore, a statistical model with a series-parallel approach was used for this purpose. This model was applied to a machine shop in the metal-mechanical sector, with a low-volume and high-mix production. The results obtained were the reliability indices for the components, the subsystems, and the man-machine system, which was useful to identify components-subsystems relationships of lower reliability and propose areas for improvement.

One hypothesis raised was the man-machine system of the machine tool is defined from the component-subsystem relationship, if the non-conforming parts present in the machine tool have been considered, their analysis and classification for a determined period must be registered. Another hypothesis raised was the reliability of the man-machine system is evaluated from the component-subsystem relationship if a statistical model considers the series-parallel systems approach. Then the objective of this paper is to present the methodology used to assess the reliability of the man-machine system in a machine tool since the man-machine system design and the selection of the appropriate statistical models and to present some improvement areas.

Methods

This kind of research is exploratory. It started considering the non-conforming parts from three machine tools. Causal Analyses and a classification system using the Cluster Analysis were used to analyze the non-conforming pieces. The methodology was the following.

Detection of subcauses of failure and the place where they occurred

The classification of non-conforming parts and the assignment of causes of failures were made to identify the subcauses for failure, the place where the failures occurred, and the a ccount for these failures. For this classification, the subcause has been named the componen t and the place where the failure occurred has named the subsystem. With the participation o f operators, technicians, and engineers from the three machine shops this analysis was done.

Selection of failures and causes for failure

A previous standardization and systematization process of the terminology used was necessary to carry out to identify the name of the failures and the causes of failure. An example of the standardized name of failures and the analysis of the causes of failures that occurred in the machining area are shown in Table 1 and Table 2 respectively.

Table 1. Example of the standardized name of failures in the machining area.

Failure
Fractured part
Large diameter
Hole out of position
Misaligned chamfer
Short distance
Depth out of specification
Embedded burr

Source: Own design

Table 2. Example of causes of failure in the machining area.

Cause of failure
Type of soluble
Insufficient knowledge
Flat misinterpretation
The poor condition of the material
Excessive force in torque
Wrong insert method
Conversion error/measurement

Source: Own design

According to the analysis of failures and the causes for failure, the subcause of failure (component) and the place where the failure occurred (subsystem) are shown in Table 3.

Table 3. Classification of components and subsystems in the machining area.

Component or Subcause	Subsystem or Place
Maintenance/Set up	Machine
Admission profile	Tool
Institutional conditions/ Attitude	Process/Operation
Information/Communication	Measurement/Instrumentation
Calibration	Programming/Design
Supplier	Material

Source: Own design

Model of the relationship between subsystems and components

Considering the classification of components, and subsystems from Table 3, a model of the component-subsystem relationship was designed. Operators, technicians, and engineers' experiences were relevant and useful to developing the analysis shown in Table 4.

Table 4. Model of the relationship between subsystems and components.

SUBSYSTEMS	SUB-CAUSES/COMPONENTS					
	Maintenance/ Set up	Admission profile	Institutional conditions/Attitude	Information/ Communication	Calibration	Supplier
Machine	X	X	X	X		X
Tool	X	X	X	X		
Process/Operation	X	X	X	X		
Measurement/Instrumentation	X	X	X	X	X	
Programming/Design		X	X	X		
Material		X	X			X

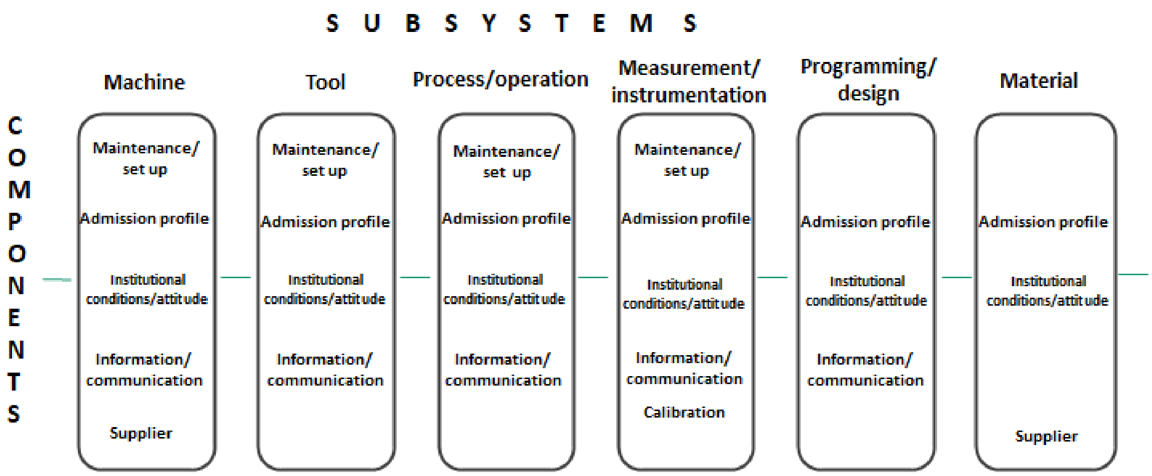
Source: Own design

Table 4 shows the contribution from components and subsystems within the failures in the machining area and they were useful to design the man-machine system model of the machining area.

Man-Machine system model of the machining area

According to the component-subsystem relationships from Table 4, the man-machine system model of the machining area from Figure 1 was designed.

Figure 1. The man-machine system of the machining area.



Source: Own design

Considering the component-subsystem relationships from Figure 1, Admission Profile and the Institutional Conditions / Attitude are present in every one of the six subsystems. At the same time, Maintenance / Set up, Supplier, Calibration, and Information / Communication, only influenced some blocks. Considering the physical structure of this system (Figure 1), a serial-parallel system approach was considered as an adequate configuration to assess its reliability. It is important to mention that for this research, the term "reliability" is used as the probability to find a product without failures for which it must be scrapped.

Reliability assessment of a component-subsystem relationship

Considering the component-subsystem relationships directly affected by the failures analysis for a certain period, the assessment of the man-machine system reliability was done. Subsystems can be affected by one or more components, as is shown in Figure 1, so the component-subsystem relationships were analyzed from times to failures and using the Weibull and Exponential reliabilities indices from Equation 1 and Equation 2 respectively for the reliability assessment of the component-subsystem relationship.

$$R(t) = e^{-\left(\frac{t}{\eta}\right)^{\beta}} \quad (1)$$

$$R(t) = e^{-\lambda t} \quad (2)$$

In Equation 1, R(t) is the reliability for a component-subsystem relationship for a Weibull distribution, η is the scale parameter and β is the shape parameter. In Equation 2, R(t) is the reliability for a component-subsystem relationship for an Exponential distribution and λ is the scale parameter.

Reliability assessment of a subsystem

According to the man-machine system from Figure 1, subsystems were distributed in a parallel configuration, and their reliability indices were determined based on their corresponding component-subsystem relationship by using a serial configuration system when the components are mutually independent (Equation 3).

$$R_s = \prod_{i=1}^{n} R_i \quad (3)$$

In Equation 3, Rs is the reliability for the subsystem, and R_i is the reliability of the component-subsystem relationship.

Reliability assessment of the Man-Machine System

The reliability assessment of the man-machine system consists of determining the reliability for each component-subsystem relationship, each subsystem, and the whole system. Thus, based on the formulated man-machine system configuration given in Figure 1, and by using the collected failure time data, the reliability of the system was determined as follows.

The reliability of a redundant or parallel system is computed in Equation 4.

$R_S = 1 - [(1 - R_1)] * [(1 - R_2)] * \ldots\ldots [(1 - R_n)]$ Generalizing for n subsystems it is:

$$R_S = 1 - \prod_{i=1}^{n}(1 - R_i) \quad (4)$$

In Equation 4, R_S is the reliability for the man-machine system, and R_i is the reliability of the subsystem. The equation for its calculation is taken for a parallel system.

A brief methodology description in 7 steps

A brief methodology of the assessment of the man-machine system proposed is:

1. The corresponding times to failure data were recorded for each failure (days or hours) and assigned to the corresponding component-subsystem relationship.

2. Considering all times to failure registered in every component-subsystem relationship, a goodness of fit test was performed to determine the best theoretical distribution and its parameters, which describes the failure behavior (Weibull or Exponential).

4. The reliability of each component-subsystem relationship was computed by using the corresponding Weibull or Exponential parameters from Equation 1 and Equation 2 respectively.

5. The reliability of each subsystem was computed by using Equation 3.

6. The reliability of the man-machine system was computed by using Equation 4.

7. Analyze and determine the lowest reliability and select the most critical component and subsystem as an opportunity area.

Results

The results of this research consisted of the implementation of the man-machine system model and the statistical models to assess its reliability in a company from the metal-mechanic sector, with a low-volume and high-mix production, using non-conforming parts considered as scrap. The implementation and validation of the methodology proposed are presented below through a case study.

Data collection

From May 17 to 28, 2021, the daily time to failure (hours) from the non-conformance product in the scrap area was analyzed. The classification of failures was used to analyze data and to determine the component-subsystem relationship presented in this period, as shown in Table 5.

Table 5. Component-subsystem relationships presented in the scrap area and their definition.

Component-subsystem relationship	Definition
1,1	Machine - Maintenance/Set up
1,6	Machine – Supplier
2,1	Tool – Maintenance/Set up
3,1	Process/Operation – Maintenance/Set up
3,3	Process/Operation – Institutional Conditions/Attitude

Source: Own design

In Table 5 the index (i,j) of each relationship depends on its location within the man-machine system from Figure 1. The subsystems have the index **i** and components have the index **j**. The combinations (1,1), (1,6), (2,1), and (3,1) depend on time and the relationship (3,3) does not depend on time.

The corresponding goodness-of-fit- tests were performed for each combination observed in the analyzed period, to determine de probability distribution and its parameters, as shown in Table 6. For this purpose, the software Weibull $^{++}$ was used.

Table 6. Parameters of failure for the component-subsystem relationships presented in the scrap area. Data from May 17 to May 28, 2021.

	WEIBULL		EXPONENTIAL
COMBINATION	β	η	λ
1,1	3.4615	7.9737	
1,6	2.18399	7.19726	
2,1	1.52633	5.32846	
3,1	1.90918	2.34728	
3,3			1/9.5

Source: Own design

Table 5 and Table 6 show that, because the combination 3,3 does not depend on time (institutional conditions/attitude), then the exponential distribution was used to assess its reliability. Thus, the assessment of the reliability of the system was analyzed using both distributions Weibull and Exponential.

Reliability of each component-subsystem relationship for the analyzed period

Using the parameters defined in Table 6, the reliability index of each component-subsystem relationship for the analyzed period was computed using Equation 1 and Equation 2 considering 5 different periods. The reliability indices are presented in Table 7.

Table 7. Reliability indices for each component-subsystem relationship considering 5 different periods. Data from May 17 to May 28, 2021.

Periods	$R_{1,1}$	$R_{1,6}$	$R_{2,1}$	$R_{3,1}$	$R_{3,3}$
1 hour	0.6478	0.7382	0.7509	0.4437	0.9000
3 hours	0.2718	0.4023	0.4234	0.0871	0.7292
5 hours	0.1141	0.2193	0.2387	0.0171	0.5907
7 hours	0.0478	0.1195	0.1346	0.0033	0.4786
9 hours	0.0200	0.0651	0.0759	0.0006	0.38776

Source: Own design

Table 7 contains the reliabilities of all component-subsystem relationships presented in the analyzed period. It shows that only three subsystems contributed to the failures (1, 2, and 3) and only 3 components contributed to the failures (1, 3, and 6). The worst reliabilities were presented in *3,1 and 1,1* relationships corresponding to process/operation-maintenance/set up and machine-maintenance/set up. Maintenance/set up was presented common participation. The reliabilities of component-subsystem relationships were used to determine the reliability of subsystems.

Reliability of the subsystem for the analyzed period

The reliability of subsystems was computed using Equation 3, considered as serial systems. Table 8 shows the reliability index for each subsystem considering 5 different periods.

Table 8. Reliability value for each subsystem considering 5 different periods.

Data from May 17 to May 28, 2021.

Periods	R_1	R_2	R_3
1 hour	0.4782	0.7509	0.3990
3 hours	0.1094	0.4234	0.0635
5 hours	0.0250	0.2387	0.0101
7 hours	0.0057	0.1346	0.0016
9 hours	0.0013	0.0759	0.0002

Source: Own design

Table 8 shows that the reliability of subsystem 1 (machine) and subsystem 3 (process/operation) are the ones with the lower reliability. However, these subsystems' reliability indices allowed determining the reliability of the man-machine system.

Reliability of the man-machine system

Based on the reliability indices from Table 8 and considering a parallel system using Equation 4 for different periods, the man-machine system reliability was analyzed, and it is shown in Table 9.

Table 9. Reliability value for the man-machine system considering 5 different periods. Data from May 17 to May 28, 2021.

Periods	R_S
1 hour	0.9219
3 hours	0.5191
5 hours	0.2653
7 hours	0.1409
9 hours	0.0773

Source: Own design

According to the Case Study analyzed and according to Table 7, in a period of three hours after the start of the shift, the component-subsystem relationships *3,1* and *1,1* referring to Process / Operation-Maintenance / set up (8.71%) and Machine-Maintenance / set up (27.18%), were the ones with the lower reliability, being Maintenance / set up the common component.

Table 8 shows that in a period of three hours after the start of the shift, in subsystem 1 (machine) the probability that there were no failures for scrap was 10.94%, while in subsystem 2 (tool) was 42.34% and in subsystem 3 (process/operation) it was 6.35%. The worst reliability was for subsystem 3. Regarding the reliability of the man-machine system from Table 9, it showed a probability of 51.91% that no scrap failures occur in three hours after starting the shift.

In the machine shop, maintenance/set up is the primary concern that must be improved. The issues that caused these low levels of reliability are attributed to the insufficient preventive and predictive maintenance program. The machine shop and its operations involved in manufacturing these parts are working to improve their machine maintenance by developing and implementing a preventive and predictive maintenance program.

Discussion

The results obtained in this research were congruent with two hypotheses raised. The first one was "The man-machine system of the machining area is defined from the component-subsystem relationship, if the non-conforming parts present in the machine tool have been considered, their analysis and classification, for a determined period". It was supported by the structured analysis of the information collected and the man-machine system design which allowed to have the conditions to be analyzed with the series-parallel system approach.

The second hypothesis raised was "The reliability of the man-machine system is evaluated from the component-subsystem relationship if a statistical model considers the series-parallel systems approach". It was supported by the Statistical models applied to assess the reliability of the component-subsystem relationship assessment with the Weibull and Exponential distributions, the subsystems assessment with a series system approach, and the man-machine system assessment with a parallel system approach.

Some limitations of this proposed methodology were the lack of records related to failures and, therefore the analysis of data. In some cases, the same failure is registered with a different name (standardization) and the data collection process is not continuous (systematization).

The information in this paper can be useful as the basis for the development of a process to improve the reliability of machine shops considering the lower reliability indices. These let us reduce the scrap rate and improve the system reliability. Regarding the evaluation of the reliability of a man-machine system, the tools used by other authors did not consider the establishment of an evaluation model based on a man-machine system designed with the characteristics of a specific machine tool area aimed to reduce scrap based on the assumptions of the Weibull and Exponential distributions.

Other authors have applied the Weibull and Exponential distributions in different contexts, methodologies, and tools from the perspective of reliability, their research work is explained below to highlight their different contributions that contrast with the contribution of this research work; both in the context of application and in the methodology used. Being common in the process reliability perspective. Zhang, Xie & Tang (2006) presented a study of the efficiency using robust regression methods over the ordinary least-squares regression method based on a Weibull probability plot. The emphasis was on the estimation of the shape parameter of the two-parameter Weibull distribution. Both the case of small data sets with outliers and the case of data sets with multiple censoring were considered. Maximumlikelihood estimation was also compared with linear regression methods. Simulation results showed that robust regression was an effective method in reducing bias and it performs well in most cases.

Flores, Torres & Alcaraz (2010) analyzed three technological alternatives to produce electricity and compress gas in offshore crude oil processing facilities to be installed in Mexico. The comparison of alternatives was made based on system reliability estimations by using the "reliability block diagram" method. The fundamental concepts of the systems reliability theory were pointed out, and the reliability model was defined as a parallel arrangement with redundancy in passive reserve and without maintenance for any component.

Assuming Weibull time-to-fail distributions cannot be correctly estimated from field data when manufacturing populations from different vintages have different failure modes, Rand & McLinn (2011) investigated the pitfalls of ongoing Weibull parameter estimation and analyzed two cases, based upon real events. Assessment of the mixed population at each month of calendar time resulted in an increasing Weibull shape parameter estimate at each assessment. When the two populations were separated and estimated properly, a better fit with more accurate estimates of Weibull shape parameters resulted.

Guevara, Valera-Cárdenas & Gómez-Camperos (2015) proposed a methodology to assess the reliability factor in the management of industrial equipment design. The complexity of several industrial procedures and the equipment required establishes that not all asset failure patterns may be easily handled through maintenance service activities done after its manufacturing and use. To avoid all kinds of high-impact failures to use the product, there must be a stage of elimination by removing some maintenance needs, and it should be done considering their own foundations from the very first moment where the asset is designed and produced.

Piña-Monarrez (2016) proposed conditional Weibull control charts using multiple linear regression. Because in Weibull analysis, the key variable to be monitored is the lower reliability index (R(t)), and because the R(t) index is completely determined by both the lower scale parameter (η) and the lower shape parameter (β).

The Weibull and Exponential distribution were used due to the beginning of the research it was assumed that the random variables involved in the failures within the man-machine system had a Weibull and Exponential behavior. As the study developed, it was found that mechanical and human error origins of failure were the most frequent occurrences in the machining area, proving these assumptions. The Weibull distribution is suitable to represent failures of mechanical origin because they are time-dependent, and the Exponential distribution represents failures of human error origin which are not time-dependent.

Conclusions

According to the structure of the man-machine system proposed in Figure 1, with serial-parallel arrangements was possible to perform reliability tests for a series-parallel system based on the component-subsystem relationships. A combination of Weibull and Exponential distributions following the proposed methodology, allowed us to determine the reliability of the system, while at the same time, determining the subsystem and/or component-subsystem relationships with the lowest reliability that should be subject to improvement.

This man-machine system was a flexible tool because it allows to include any quantity of components and subsystems, according to the analysis of failures in any period. Once the man-machine system was designed, using the series-parallel system approach proposed to assess the reliability of the man-machine system turned out to be efficient.

The man-machine system and the statistical model can be adapted to any company from the metal-mechanic sector, with a low-volume and high-mix production whose operations are carried out on conventional and CNC machine equipment that utilizes the characteristics of batch production. The man-machine system reliability indicators provide useful information that must be monitored over time. Not having this indicator would be working blindly and aimlessly.

The effectiveness of this method to determine the reliability of the man-machine system is supported by the fact that in this system the variables that generate the failures are mainly time-dependent (process/operation-maintenance/set up).

In applying this proposed method, the efficiency of the reliability calculation depends on the parameters of the distributions used, given that there is a discontinuity in the type of work and workload in the man-machine system. The same combination does not always occur, and it is necessary to monitor the parameters of this distribution, although this does not allow continuity. Thus, the real challenge is to analyze the occurrence of each combination that occurs in the failure analysis in each period and provide a solution. The effectiveness of the proposed method could be increased if, instead of using censored times (9.5 hours), full times were used.

The methods used by other authors for the evaluation of the reliability of the man-machine system are not based on the occurrence of failures or on the series-parallel configuration, they use a technique to evaluate a certain system already established, but they do not establish their own system of study, as is this methodology so, this methodology is novel.

Further research

In the application of the proposed method, the analysis would require further research if whether machines producing large batches or continuous production are analyzed to know if the proposed methodology can be applied to this type of production and be able to extend its reach. It is highlighted that although in continuous production, as in Piña-Monarrez (2016), the Weibull parameters can be used to monitor if the process remains in control and the non-normal capability (cp) and ability (cpk) indices derived in Piña-Monarrez et. al. (2015), can be implemented, due to the complex combinations of the serial-parallel configuration of the machine shops, more research must be undertaken.

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