Model for fault detection and simulation under maintenance and project management

Modelo para detección y simulación de fallas bajo la gestión de mantenimiento y proyectos

Javier Augusto Barros Leal[1*]
Julio César Martínez Espinosa[2]

[1] Colombian MsC. International Iberoamerican University. * Corresponding author correspondencia.
E-mail: jaubale07@hotmail.com

[2] Mexicano. PhD. Universidad Internacional Iberoamericana.

Abstract

This paper presents the design and implementation of a model based on a device that contains elements of digital control and integrates an automatic detection and fault diagnosis system that can be used as a tool for the orientation of operators during the presence of a potential failure. This system is based on digital control under the implementation of a data acquisition card (DAQ) and programmable application software. With the completion of this study, a contribution is made to the development of total productive maintenance and its scope is aimed at contributing significantly to autonomous maintenance.

Keywords: autonomous maintenance; fault detection; simulation; DAQ.

Resumen

En este trabajo se presenta el diseño e implementación de un modelo basado en un dispositivo que contiene elementos de control digital e integra un sistema automático de detección y diagnóstico de fallas que puede ser usado como herramienta para la orientación de los operarios durante la presencia de una falla potencial. Este sistema se fundamenta en el control digital bajo la implementación de una tarjeta de adquisición de datos (DAQ) y un software aplicativo programable. Con la realización de este estudio se hace un aporte al desarrollo del mantenimiento productivo total y su alcance va dirigido a contribuir significativamente en el mantenimiento autónomo.

Palabras clave: mantenimiento autónomo; detección de fallas; simulación; DAQ.

Introduction

A fault is a temporary or definitive interruption of the system, which generates a disturbance within the development of an industrial process or process (Vallejo 2016). The impact generated by these events depends on their frequency of occurrence and at the time of response to their solution, a well-defined maintenance program applied to a production system can reduce the risk of failure (Montenegro, Velásquez and Pérez, 2016). The perturbations suffered by the processes from the moments before a failure event, cause variations in the nominal values of their variables to the point of causing a minor failure to a suspension of plant activities (known as plant shutdown).

Ante e Given this circumstance, a series of questions arise within the vast majority of productive systems, namely: How can downtime and other maintenance costs be reduced? How can systems be increased? In what way can operational personnel be trained without compromising production, raising maintenance costs and putting equipment at risk? In all cases, procedures are required to guide the activities to be carried out and trained personnel for its execution, giving the joint action of operators and maintenance personnel, inspired by the autonomous maintenance. The idea of autonomous maintenance is that each operator knows how to diagnose and prevent possible failures of his equipment and thus prolong its useful life (Aguilar, 2013).

In this study a model for detection and simulation of failures in production systems is implemented under the focus of maintenance management and projects, which will enable training of operational staff and improve the performance of maintenance personnel under the figure of simulation of failures without putting the integrity of the equipment at risk and without generating maintenance costs. In addition, it proposes a solution to the problem where downtime is great, due to the delay to intervene in the equipment for reasons other than the techniques.

The model consists of seven stages (See Figure 1) developed sequentially, which are executed in two phases; a methodological phase and an application phase. In the methodological phase, it includes the preparation of a diagnosis of the current state of the productive system related to the maintenance factor, the hierarchy and identification of the equipment considered critical and the determination of the failure modes in those components.

Figure 1. Stages of the model
Source: the authors.

In the application phase, the design of a prototype is made up of an interface card that operates in conjunction with an application software, which is used to guide the operators in the initial attention of a fault, thus preventing it from being prolonged and therefore , to minimize the effects produced by the unexpected failure events that occur within the productive processes that are carried out in the manufacturing companies.

The model is aimed at those productive systems that are located in remote and difficult to access places that have problems to solve faults in their equipment, where it can take many hours or even days to start the attention of a fault. This is the case of the Colombian-Venezuelan border zone, the contextual framework where this research was developed, where there are many inconveniences to move from one side to the other of the border axis, which makes it very difficult to solve an anomaly presented in one of those systems products that are located there.

Although there are several studies characteristic of the region, there is no background of studies related to the issue of failures in the productive systems, considering the conjunctural situations of commercial exchange an element that makes it difficult to reach it, due to the high level of existing informality.

The model was implemented in the company belonging to the plastics industry of the Colombian-Venezuelan border area, where the problems inherent to commercial exchange prevent the opportune attention of anomalies with external personnel, forcing the operative personnel to be trained in the solution and treatment of equipment failures, to reduce production costs.

Materials and methods

Stage I. Initial diagnosis

Inherent factors are identified to the functions developed within a productive system by production and maintenance personnel, related to downtime, failure events, maintenance management, fault detection, among others.

To obtain information, surveys and personalized interviews were applied; likewise, the logs registers contribute in large part to the collection of information.

In the characterization of the maintenance function in the productive systems of the Colombian-Venezuelan border zone, about 20 companies participated, which were classified according to their activity as detailed in Table 1.

Table 1. Description of the productive systems participating in the diagnosis

DESCRIPTION	TOTAL
1. The main activity of the productive system	
a. Goods and service	5
b. Health	1
c. Ceramic industry	1
d. Electrification	2
e. Cement	1
f. Plastic	6
g. Printing	1
h. Metalworking	3
2. Running maintenance programs	
a. None	12
b. Some or partial	5
c. Total or advanced	3
3. Execution of maintenance activities	
a. Only corrective	12
b. Preventive / corrective	7
c. Other (predictive / proactive)	1

4. Event/failure logs and relevant information

a.	It does not exist/does not carry	13
b.	It has some information	5
c.	It has information	2

Source: the authors.

The application of an instrument consisting of 22 questions with four response options (Always, Almost Always, Sometimes and Null), was applied to 121 people from the operation and maintenance areas of companies located in the contextual framework, as a multidisciplinary component of the population and in addition to the amount of the sample required.

The designed survey allowed the evaluation of four study variables defined to guide the research towards the simulation phase and which are related to maintenance management, fault detection, simulation, and project management.

Stage II and III. Definition of criteria and selection of criticality method

The criticality analysis is a methodology that allows establishing the hierarchy of priorities of processes, systems, and equipment, creating a structure that facilitates the making of accurate and effective decisions, directing the effort and resources in areas where it is most important and/or necessary improve operational reliability, based on current reality (Moubray, 2004, Riveros and Rosas, 2009). In order to know the impact generated by the failures in the equipment, operational, technical, environmental and other criteria are evaluated. Additionally, a quantitative method was used to determine the degree of criticality that each component possesses.

The analysis of several existing methods and used in investigations (Del Castillo, Brito-Ballina, and Fraga, 2009, Riveros and Rosas, 2009), facilitated the selection of one of them that resembled the operating conditions and the environment where locates the productive system to study.

For the implementation of this stage of the model, the method presented by Huerta (2005) was used, because this author assumes criteria that are in agreement with the application context where the research was carried out. The criteria to be evaluated correspond to off-duty, economic times, failure rate, safety, environment, repair time, production, operation and maintenance costs.

Stage IV and V. Criticality analysis and determination of the hierarchical list

The criticality analysis allows to identify and rank those teams within a plant, with the purpose of establishing priorities in the planning of the use of the resources and the maintenance actions associated with them (Díaz, Pérez, del Castillo and Brito 2012; 2013, Espinosa, Salinas and Leiva, 2010). Its determination corresponds to equation 1.

$$Criticality = Frequency\ of\ faults\ \ Consequence\ of\ faults\ (1)$$

$$Consequence = a + b$$

Where:
a = cost of repair + impact of personal safety + environmental impact + impact of customer satisfaction
b = impact on production × Average time to repair MTTR

The factors that are part of the equation correspond to:

Fault frequency: Number of times an event is repeated or fails within a period of time.

Operational impact: Effects caused by production failures.

Average time to repair: Possibility of making changes, repairs quickly to continue production without incurring significant losses of time.

Cost of maintenance: Costs inherent to the maintenance factor, does not include the production costs experienced by the failure.

Impact of security: Potential consequences of failures on the health and safety of people.

Impact environment: Potential consequences of failures on the environment.

Impact of customer satisfaction: Understood as the effects produced by failures due to economic losses in the other areas of the company and that causes nonconformities to third parties.

The equipment to be taken into account for the following stages of the criticality analysis correspond to those that are classified as high and very high criticality.

In relation to the criticality values, ranges are defined according to the frequency levels, in correspondence with the average values of the consequence factors, expressed in the criticality equation. In table 2 shows the values defined for the implementation of the present model.

Table 2. Levels of frequency and consequence in the criticality equation

Frequency level	Consequence range	Criticality value
1	Less than 30	Low criticality
2	Between 30 and 50	Low criticality
3	Between 50 and 70	Medium criticality
4	Between 70 y and 90	High criticality
5	Older than 90	Very high criticality

Source: the authors.

The hierarchical list is determined according to the levels established in the criticality matrix defined for the equipment, which is shown in Figure 2.
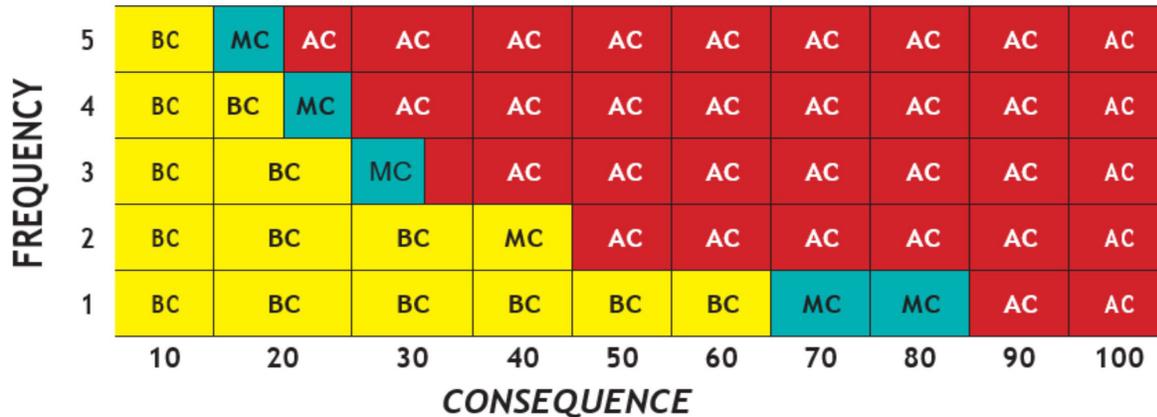

Figure 2. Criticality matrix defined
Source: the authors.

The equipment to be analyzed by the criticality method was classified into four areas taking into account their location in the production process of the company and identifying a total of 61 components that are listed in Table 3.

Table 3. List of equipment for criticality analysis

LOCATION	EQUIPMENT	QUANTITY
Compressors area	Compressed air unit	2
Mixing area	Industrial mixers	2
Mixing area	Semi-industrial mixers	1
Extrusion area	Injection machines bags	6
Extrusion area	Injection machines pots	3
Extrusion area	Vessel injection machines	3
Extrusion area	Extrusion machines	6
Packing area	Mooring machines	3
Packing area	Cutting machines	3
Packing area	Packaging machines	3
Packing area	Gluing machines	2
Packing area	Sealing machines	6
Pelletizing area	Pelletizing machines	2
Control and command area	Bank of transformers	2
Control and command area	Electrical substation	1
Control and command area	Main control boards	4
Control and command area	Secondary control panels	12

Source: the authors.

The information required for the defined criteria corresponded to records obtained during a period of four months, considering failures and downtime.

Hierarchy The final results of the criticality of the teams leads to the structure of the hierarchical list of the productive system. This allowed knowing the components that require more attention and to those that should be available and direct the greatest efforts and resources within the productive chain of the organization.

Impact of faults. The out-of-service times of critical equipment that originate from the respective failure modes or "Events" are quantified. These times will allow calculating the reflected losses of the equipment in terms of its production capacity. It is recommended to establish a reference time of at least three to six months to evaluate the impact generated by the failures.

Stage VI. Analysis of modes and effect of faults (AMEF)

The potential failures of the critical equipment are identified, analyzed and evaluated, giving them a priority and appropriate attention, according to the impact that they may generate. This technique guides the elaboration of operational conventions and faults attention protocols for incorporation into the database of the projected simulation stage.

Initially, the functions, operating parameters, functional faults and effects generated in the equipment selected as critical from their operational context must be identified.

The data of the operational characteristics of the equipment to be analyzed and the events, faults and other necessary data, will be taken from the specifications of the plate, logs, manuals of manufacturers, technical catalogs and also information provided by the company's personnel.

Stage VII. Simulation stage

The operational slogans established from the previous phase are incorporated into the database of the application software that interacts with the physical interface designed to complement the project.

Software implementation and prototype. This stage involves four elements: logical-sequential approach and selection of elements, the design of the logic-analog interface, development of the computational tool and elaboration of tests of the joint systems.

Logical-sequential approach and selection of elements. The coupling of signals to the projected system in the discrete form (signals of 0 or 5 V of direct current), number of variables that intervene in the processes, operating protocols, preparation of operational slogans, simplification of functions and determination of components. The parameters used in the different stages of the system correspond to voltage signals between 1.5 and 5.5 volts of direct current and current signals between 4 and 20 milliamperes of direct current.

The electronic components that integrate the control circuits of the system variables are transistor-transistor logic technology or TTL (for its acronym in English) powered through a 5.5 V DC source at a capacity of 2 amp current. The handling of the signals in the input stage of the simulator corresponds to discrete signals that operate between 1.2 and 5.5 V in direct current.

Design of the logic-analog interface. The interface designed for the handling of input/output data is based on a card for data acquisition under the RaspBerry Pi 3 Model B system or low-cost single-board SBC (Single Base Computer). Two circuits are incorporated: the input module (analog and discrete signals) and the output module. Interconnected through 8-bit data buses, with integrated circuit Buffer 8 line TTL technology drivers referenced as DM74LS244.

In the detection function, twelve analog-digital signals from sensor elements of the equipment installed in the processes are handled. For the fault simulation function, there are 12 logic switches, a variable voltage

signal, and a level control circuit, whose activation resembles that sent by the sensors coupled to the equipment (see Figure 3).
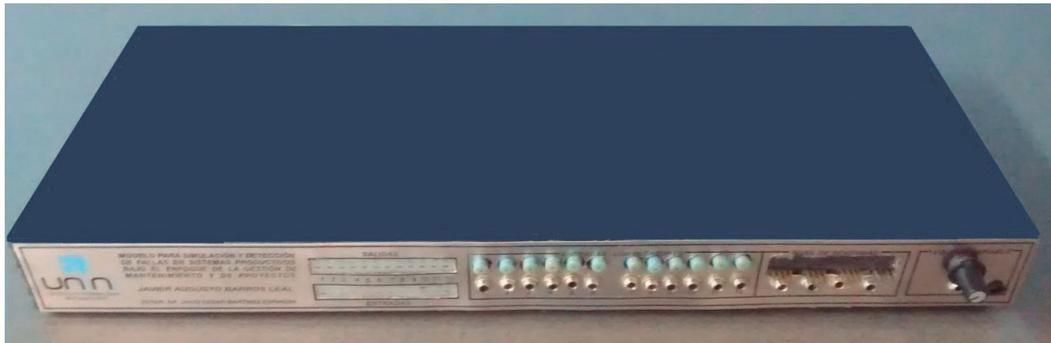

Figure 3. Device Interface of the model
Source: the authors.

Determination and development of the computational tool. The application used for the processing of data, signals and information management was developed based on the Raspbian operating system version 4.1.

The application program is able to be programmed to configure a number of different processes, limited by the existing memory capacity for the database. Each process handles a large number of different types of failures per equipment; with their respective modes, causes, and actions that the operator must perform during the treatment of an anomaly.

The skill in the operation of the software as a simulator function will serve to train staff in a shorter time without putting equipment at risk, achieving optimal results in the solution of faults thereof and their understanding will bring advances in autonomous maintenance. Figure 4 shows the initial window designed in the application software that is part of the proposed model.

Figure 4. Application software screen
Source: the authors.

Elaboration of tests of the joint systems. Developed the systems in an independent way, the tables corresponding to the treatment of the faults that will be incorporated in the database of the application software were elaborated. To arrive at this, the results of the diagnosis band the analysis of the modes and effects of the faults were taken into account, the information of which generates a procedure for their attention.

The procedures are encoded in binary form to exchange information with the external devices of the interface and thus carry out the simulation of faults.

Simulation, implementation of the final model. The operational variables of the process were analyzed, to establish the data obtained under fault conditions and to determine the tables equivalent to them, to finally carry out the implementation of the model proposed as the object of the investigation.

An important and novel feature of the project in regard to the interface is that it can be accessed from any point and place, through the internet platform if it is installed within a network of computers. This in order to monitor and control in remote mode.

The web application "Trainer" (Barros, 2017) was developed, as a free version of the software that is part of the model and that only works in simulation mode (when the interface is not available), to be used by those interested production systems to use this tool in the training of the personnel of their companies, in solution and attention of failures according to the conditions of their processes. Likewise, a link to a website has been provided within this application, where the full version of the application software can be downloaded as a structural part of the project's scientific contribution and which is aimed at all those productive systems that wish to implement the model in its full version.

Results

Stage 1. Initial diagnosis. Figure 5 presents the results of the aspects that characterize the management of maintenance in the evaluated production systems.
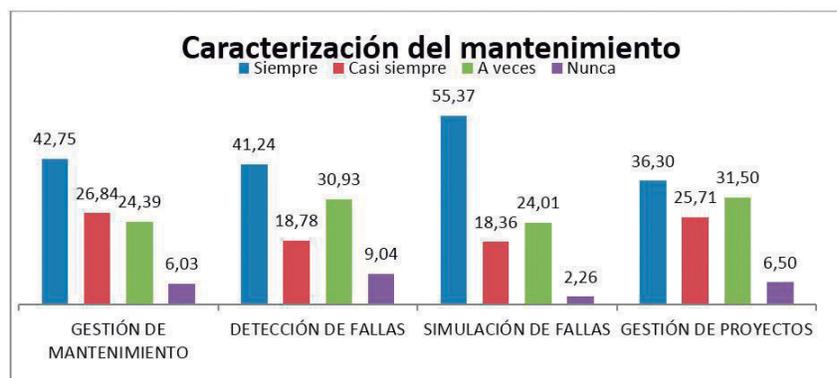

Figure 5. Variable results maintenance management
Source: the authors.

The results presented, identify that in 69.59 % of the cases, moderate management is carried out in the maintenance actions (always 42.75 % and almost always 26.84 %), predominating the use of resources, tools and elements of work and safety with a high willingness to participate in training programs and teamwork.

For the variable detection of failures, in 60.02 % of the cases (always 41.24 % and almost always 18.78 %), the handling of parameters of characteristic variables in the processes intervenes, although in the majority of cases, allowable ranges are controlled empirically because of the low technical level in the control thereof, which causes the presence of a large number of fault events.

The 73.73 % of the surveyed personnel (always 55.37 % and almost always 18.36 %), in the simulation variable agrees on the need to follow operating protocols to develop the processes, understand what each maneuver is performed for to the stages of them; however, in most of the production systems, the operation and maintainability of the equipment is not documented.

With regard to the variable project management, 52.01 % of the cases (always 36.30 % and almost always 25.71 %) manifests in its responses that own actions are carried out that are part of the scope, resources and time management in operation and maintenance actions (characteristics of project management), as a result of the relationship that activities have developed individually either by processes or equipment, which can be conceived as microprojects and that added together, can integrate a global management process to a macro project.

The characterization of the maintenance function shows that there is room for improvement. The overall percentages of the study variables, although moderate, are not the most optimal at the time of evaluation.

Validation of the sample. In the determination of reliability of the measurement and instrument of the investigation, the Cronbach's Alpha method was applied and its result was verified by the SPSS Software, whose value is shown in Table 4.

Table 4. Scale: Reliability of data and instrument

SUMMARY OF CASE PROCESSING			
		N	%
Cases	Valid	118	100,0
	Excluded*	0	0
	Total	118	100,0
* The elimination by list is based on all the variables of the procedure			

RELIABILITY STATISTICS	
Cronbach's Alpha	No. of elements
0,819	22

Source: the authors, with data obtained from SPSS software (2017).

Reliability of the data obtained by verifying the result respecting the following recommendations for assessing Cronbach's alpha coefficients is evidenced, as general criteria the following values are suggested: Alpha coefficient > 0.9 is excellent,> 0.8 is good, > 0.7 is acceptable (George and Mallery, 2003; Frías-Navarro, 2011; Lamprea and Gómez, 2007).

Regarding the total validity, 0.9092 is obtained taking into account three fundamental aspects: validity of the content of the instrument, the validity of the criteria and validity of the construct (Questionnaire questions), in the sum of the partial values of each of them.

The variability of the data with respect to the variables is shown in Table 5.

Table 5. Variability of the data in relation to the research variables

VARIABLE	STANDARD DEVIATION	AVERAGE	COEFFICIENT OF VARIABILITY
Maintenance management	12,2 %	0,78	16 %
Fault detection	6,6 %	0,88	7 %
Fault simulation	12 %	0,67	18 %
Maintenance management	9 %	0,93	9 %

Source: the authors.

Criticality analysis. Table 6 presents the result in the criticality assessment at the high and medium criticality levels.

Table 6. Results of the analysis obtained in the levels of high and medium criticality

MADE IN	Production and maintenance area	
YEAR:	2017	
CRITICITY LEVEL	UNIT / EQUIPMENT	CRITICITY
High	Compressed air unit	123
High	Extruder machines 1	119,4
High	Compressed air unit	96,8
High	Extruder machines 2	84
High	Pelletizing machines	72,8
Half	Industrial mixers	68,1
Half	Vessel injection machines	65,4
Half	Injection machines pots	65,4
Half	Injection machines bags	65,4

Source: the authors.

The selection of the equipment that will be part of the analysis of modes and effects of failure correspond to those that resulted as medium and high criticality for which the compressed air unit and the extruder machines are chosen.

Impact of faults. Table 7 shows the monthly ratio of the production capacity losses of the extruder machines analyzed and Table 8 details the case of the compressor unit.

Table 7. Off-duty times in extruders due to fault events

PERIOD /MONTHS (2016-2017)	TIME OUT OF SERVICE (2 Teams)	LOST OF PRODUCTION (60 Kg/hour)	AMOUNT OF BAGS Approximate (65 Kg = 1000)
NOVEMBER	84,2	5,052	77,723
DECEMBER	62,4	3,744	57,600
JANUARY	34,6	2,076	31,938
FEBRUARY	48,6	2,916	44,862

Source: the authors.

Table 8. Off-duty times in the compressor unit due to fault events

PERIOD /MONTHS Years 2016-2017	Time out of service	Loss of production extruders (60 Kg/hour) * 4 units	Loss of production equipment making pots (35 kg/hour) ** 2 units	Loss of production equipment making bags (40 kg/hour) * 2 units	Loss of production equipment elaborate glasses (30 kg/hour) *2 units	Total loss of production (Kg)
NOVEMBER	28,3	6,792	1,981	2,264	1,698	12,763
DECEMBER	19,8	4,752	1,386	1,584	1,188	8,930
JANUARY	8,6	2,064	602	688	516	3,879
FEBRUARY	14,5	3,480	1,015	1,160	870	6,540

Source: the authors.

The data only detail the production losses; they do not include the costs of repair, the raw material for reprocessing, additional energy and other aspects that multiply the production costs and that is not visualized at first hand what a failure affects the profitability of the productive systems. **Analysis of failure modes and effects.**

Figure 6 shows the result of the analysis of failure modes and effects during the operation of the simulation stage in detection-simulation mode.
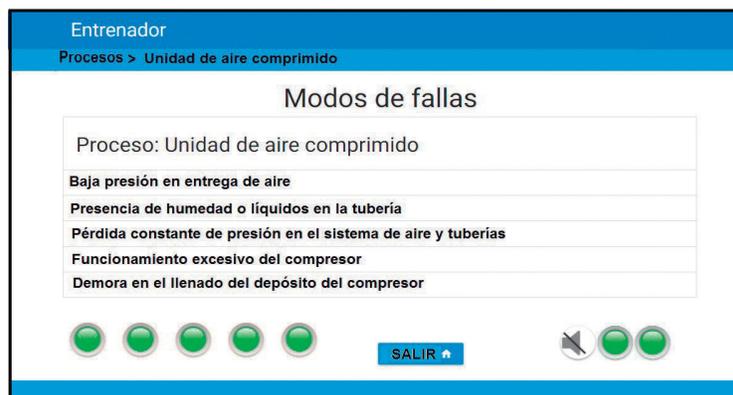

Figure 6. Failure mode in the simulation stage
Source: the authors.

Advances in autonomous maintenance. Table 9 shows the results of the reduction of failures in the equipment that turned out to be critical, once the model was implemented in the productive system studied.

Table 9. Values of reduction of fault events in critical equipment

Time/Equipment	Extruders		Compressor unit	
Months (2016-2017)	Time out of service	Number of events	Time out of service	Number of events
Noviembre	84,2	109	28,3	50
Diciembre	62,4	94	19,8	42
Enero	34,6	80	8,6	29
Febrero	48,6	90	14,5	36

Source: the authors.

There is a noticeable reduction in the intervention to the critical equipment and therefore an improvement in production costs and in the profitability of the business of the evaluated productive system is given, due to needing less the services of external personnel to lend the maintenance services to the company.

In both cases, a small value is observed in the times out of service during the interval of the months of December-January, and an increase thereof in the following month. This is due to the fact that in that month only 18 days were worked due to the effect of the New Year's holiday period that the company was not working on.

The process of adaptation of the operating personnel in autonomous maintenance produces a progressive decrease both in the times out of service and in the events of failure in the critical equipment. This response to the initial hypothesis of the investigation, where it was stated that the advances in autonomous maintenance improved the downtime and the failure events.

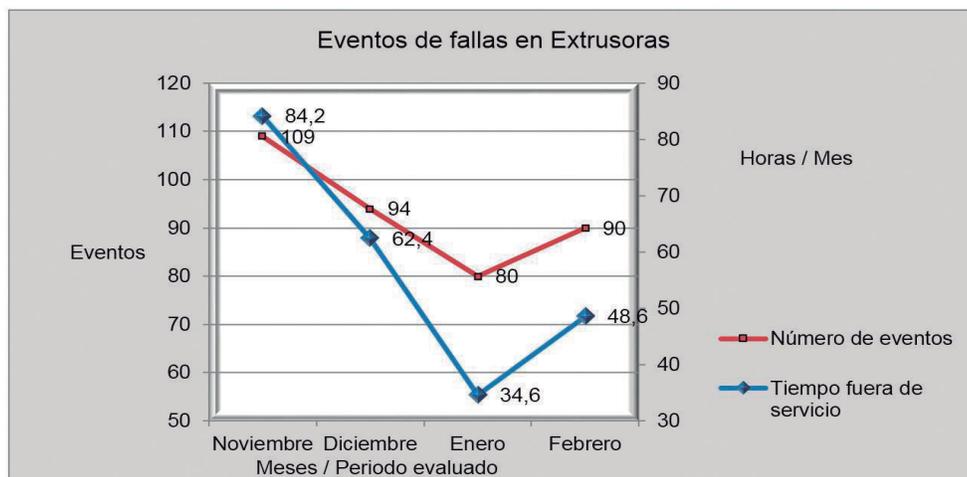Figures 7 and 8 allow visualizing the reduction results in critical equipment.

Figure 7. Fault events in extruder equipment
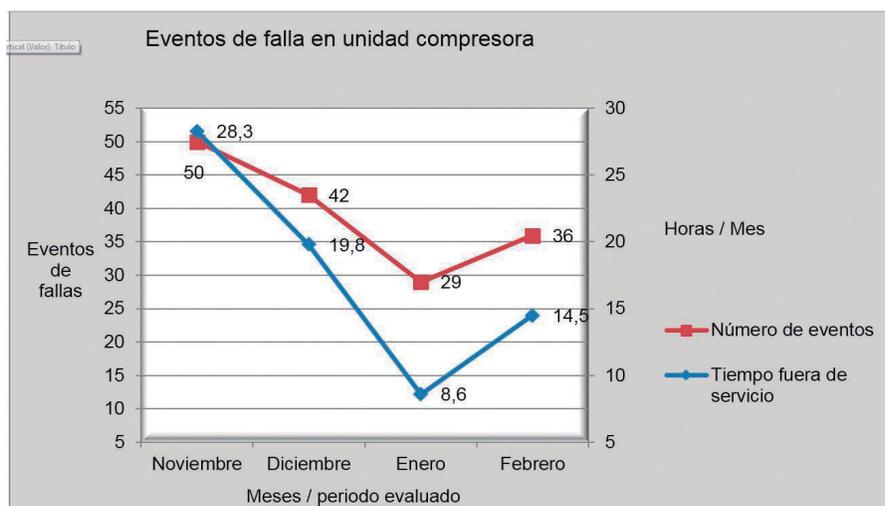Source: the authors.

Figure 8. Fault events in extruder equipment
Source: the authors.

23

Conclusions

The procedures used to determine the critical equipment of the production system under study helped to detect shortcomings in the process in terms of operation of the equipment at times where there were variations in voltages, which caused constant blockages and resulted in considerable losses of time and unnecessary expenses that affected the profitability of the company. In addition, it allowed proposing corrective actions to obtain better results in production.

The results that are pursued with the implementation of the model in advance of autonomous maintenance, establish actions that involve management based on quality, risk, resources, communications and costs among others, aspects that start from the elements of project management.

It was possible to show the people who are part of the company, how the failures of the equipment are associated with the profitability of the business, as part of the process of raising awareness towards operational reliability. In this sense, the need to initiate a training program for personnel in the stages of the process was clearly perceived, as well as the benefits associated with autonomous maintenance.

The use of computer tools for the training of personnel and for the handling of information has a positive impact on maintenance management, improves the consultation and management of the records and information of the equipment by the users. The registered information allowed reducing the effects of staff turnover and the loss of experience that this causes.

This study is the starting point to develop a culture of maintenance in the company, since it is necessary to implement different types of activities, such as inspections, lubrications, and small-scale corrective actions, to guarantee an effective improvement in the production equipment, prevent or minimize failures, avoid costly repairs and production losses due to unscheduled stops.

The detection of secondary aspects that affected the operation of the equipment, and that had not been identified, generated improvement plans, programming of equipment startup that reduced the time of suspension of the operation of the plant by around 45 %, expanding the production capacity of the plant, generating greater job opportunities for staff and increasing the profitability of the company under study.

References

Aguilar, J. y Monasterio, L. (2013). *Propuesta de un plan de mejoras que permita reducir los tiempos de paradas no planificadas en la línea de envasado n 10 en la empresa Cervecería Polar C.A., San Joaquín.* (Tesis de pregrado). Universidad José Antonio Páez, Fac. de ingeniería. San Diego, Venezuela.115 pp. Recuperado de: https://bibliovirtualujap.files.wordpress.com/2013/05/teg-aguiar-monasterio.pdf

Barros, J. A. (2017). Entrenador (Versión 1) "Software". Recuperado de: http://jaubale07.pythonanywhere.com/

Del Castillo Serpa, A. M., Brito-Ballina, M. L. y Fraga Guerra, E. (2009). Análisis de criticidad personalizados. *Ingeniería Mecánica.* 12(3), 1-12. Recuperado de: http://www.ingenieriamecanica.cujae.edu.cu/index.php/revistaim/article/view/72/395.

Díaz, Pérez, del Castillo y Brito (2012). Propuesta de un modelo para el análisis de criticidad en plantas de productos biológicos. *Ingeniería Mecánica.* 15(1), 34-43. ISSN 1815-5944. Recuperado de: http://scielo.sld.cu/pdf/im/v15n1/im04112.pdf]

Espinosa, F. F., Salinas, G. E., y Leiva, P. P. (2010). Jerarquización del reemplazo de equipos productivos de acuerdo a su nivel de cumplimiento de los objetivos de la empresa Inf. tecnol. *Ingeniare. Revista chilena de ingeniería.* 22(4), 97-106. ISSN 0718-0764. Recuperado de: https://scielo.conicyt.cl/cgi-bin/wxis.exe/iah/?IsisScript=iah/iah.xis&base=article%5Edlibrary&format=iso.pft&lang=e&nextAction=lnk&indexSearch=AU&exprSearch=SALINAS,+GONZALO+E

Frías-Navarro, D. (2011). Alfa de Cronbach y consistencia interna de los ítems de un instrumento de medida. España, Universidad de Valencia. Recuperado de:
www.uv.es/~friasnav/AlfaCronbach.pdf

George, D. y Mallery, P. (2003). *SPSS for Windows step by step: A simple guide and reference. 11.0 update.* (4th ed.). Boston: Allyn & Bacon.

Huerta Mendoza, R. (2005). "El Análisis de Criticidad, una metodología para mejorar la confiabilidad operacional". *Club de Mantenimiento.* p 12. Recuperado de:
http://www.mantenimientoplanificado.com/Articulos%20gesti%C3%B3n%20mantenimiento_archivos/de%20confiabilidad/ANALISIS%20DE%20CRITICIDAD.pdf

Lamprea, J.A., y Gómez Restrepo, C. (2007). Validez en la evaluación de escalas. *Revista Colombiana de Psiquiatría*, 36 (2), 340-348.

Montenegro Martínez, S.R., Velásquez Meza, R. I., y Pérez Gutiérrez, J. M. (2016). *Diseño de un plan de mantenimiento preventivo para el área de secado mecánico en Exportadora ATLANTIC SA, Beneficio seco de Condega en el II Semestre 2016.* (Tesis doctoral). Universidad Nacional Autónoma de Nicaragua, Managua. 148 pp. Recuperado de:
http://repositorio.unan.edu.ni/6868/1/17872.pdf

Montes, J. D. (2013). *Diseño de un plan de mantenimiento para la flota articulada de integra S.A. usando algunas herramientas del mantenimiento centrado en la confiabilidad (RCM).* (Tesis de pregado). Universidad Tecnológica de Pereira, Fac. Ingeniería Mecánica. Pereira, Colombia, 132pp.

Moubray, J. (2004). *Mantenimiento Centrado en Confiabilidad.* ISBN 095 39603–2–3. Gran Bretaña: Aladon Ltda.

Riveros, M. L. y Rosas, E. G (2009). *Diseño de un sistema de mantenimiento con base en análisis de criticidad y análisis de modos y efectos de falla en la planta de coque de fabricación primaria en la empresa Acerías Paz del Río S.A.* (Tesis de maestría). Universidad Pedagógica y Tecnológica de Colombia. Recuperado de:
http://www.uptc.edu.co.

Vallejo, C. (2016). *Diseñar un plan de mantenimiento a una rebobinadora de papel de la compañía Papeles Nacionales S.A. bajo los lineamientos de mantenimiento preventivo y predictivo.* (Tesis de pregrado)Universidad Tecnológica de Pereira, Fac. Ingeniería Mecánica. Pereira, Colombia. 54 pp. Recuperado de:
http://repositorio.utp.edu.co/dspace/handle/11059/7459