

**IMPROVING PREDICTIVE MAINTENANCE BENEFITS FROM ONLINE
MONITORING OF SPINDLES: CASE STUDY IN WOODWORKING MACHINE
TOOL**

**MELHORANDO OS BENEFÍCIOS DA MANUTENÇÃO PREDITIVA COM O
MONITORAMENTO ONLINE DE SPINDLES: ESTUDO DE CASO EM
MÁQUINAS-FERRAMENTA PARA USINAGEM DE MADEIRA**

**MEJORA DE LOS BENEFICIOS DEL MANTENIMIENTO PREDICTIVO
MEDIANTE LA SUPERVISIÓN EN LÍNEA DE LOS HUSILLOS: ESTUDIO DE
CASO EN UNA MÁQUINA HERRAMIENTA PARA TRABAJAR LA MADERA**

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Abstract

Objective: This article aims to present a case study of the application of an online monitoring system for spindles in a furniture industry, analyzing the benefits to predictive maintenance and business.

Methodology/approach: A literature review was carried out followed by a case study

Originality/Relevance: Focusing the development of maintenance techniques, especially predictive maintenance and those supported by enabling technologies from Industry 4.0, such as Internet of Things (IoT), it may be possible to carry out online monitoring of spindles with a focus on reducing catastrophic or unplanned events.

Main results: The main results are to know the normal behavior of the machine, the possibility of obtaining information in real time, managerial data for sight management, and the possibility of identifying spindle failure before it becomes a catastrophic failure, thus reducing the costs of maintaining the spindles.

Theoretical contributions: As a contribution, we discuss the development of the system to digitize the data through the operation available in an outsourced cloud environment. This data can then be returned to the company in the form of dashboards for cash management, developing agility in decision making to facilitate the predictive maintenance in addition to validating the online monitoring system for spindle management in furniture industry processes.

Keywords: Spindle, Maintenance, Industry 4.0, Online Monitoring, Internet of Things, IoT

Resumo

Objetivo: Este artigo visa apresentar um estudo de caso da aplicação de um sistema de monitoramento online para spindles em uma indústria de móveis, analisando os benefícios para a manutenção preditiva e os negócios.

Metodologia: Foi realizada uma revisão de literatura seguida de um estudo de caso.

Relevância: Focando o desenvolvimento de técnicas de manutenção, especialmente manutenção preditiva e aquelas suportadas por tecnologias habilitadas da Indústria 4.0, como Internet das Coisas (IoT), pode ser possível realizar o monitoramento on-line de fusos com foco na redução de eventos catastróficos ou não planejados.

Resultados: Os principais resultados são conhecer o comportamento normal da máquina, a possibilidade de obter informações em tempo real, dados gerenciais para o gerenciamento da visão e a possibilidade de identificar falha do fuso antes que se torne uma falha catastrófica, reduzindo assim os custos de manutenção dos fusos.

Contribuições: Como uma contribuição, discutimos o desenvolvimento do sistema para digitalizar os dados através da operação disponível em um ambiente de nuvem terceirizada. Estes dados podem então ser devolvidos à empresa na forma de painéis de controle para gerenciamento de caixa, desenvolvendo agilidade na tomada de decisões para facilitar a

manutenção preditiva, além de validar o sistema de monitoramento online para gerenciamento de fusos nos processos da indústria moveleira.

Palavras-Chaves: Spindle, Manutenção, Indústria 4.0, Monitoramento Online, Internet das coisas, IoT

Resumen

Propósito: El objetivo de este artículo es presentar un estudio de caso de la aplicación de un sistema de vigilancia en línea de los husos en una industria del mueble, analizando los beneficios para el mantenimiento predictivo y los negocios.

Metodología: Se realizó una revisión de la literatura seguida de un estudio de caso.

Relevancia: Centrándose en el desarrollo de técnicas de mantenimiento, especialmente el mantenimiento predictivo y las apoyadas por las tecnologías habilitadas por la Industria 4.0, como la Internet de las Cosas (IO), puede ser posible realizar una vigilancia de husos en línea centrada en la reducción de eventos catastróficos o no planificados.

Resultados: Los principales resultados son conocer el comportamiento normal de la máquina, la posibilidad de obtener información en tiempo real, los datos de gestión para la gestión de la visión y la posibilidad de identificar el fallo del husillo antes de que se convierta en un fallo catastrófico, reduciendo así los costes de mantenimiento del husillo

Contribuciones: Como contribución, discutimos el desarrollo del sistema para digitalizar los datos a través de la operación disponible en un entorno de nubes subcontratado. Estos datos pueden devolverse a la empresa en forma de cuadros de mando para la gestión del efectivo, desarrollando la agilidad en la toma de decisiones para facilitar el mantenimiento predictivo, y validando el sistema de supervisión en línea para la gestión de los husos en los procesos de la industria del mueble.

Palabras clave: Huso, Mantenimiento, Industria 4.0, Monitoreo en línea, Internet de las cosas, IoT

1. INTRODUCTION

With the development of production processes over the last decades, machining machines have evolved to become high-performing as well as highly-productive CNC (Computer Numerical Control) machines. Xu (2017) presents the evolution of these machines in each of the industrial revolutions and proposes the Machine Tools 4.0 model, indicating it as a necessary transformation in the current machinery plants for the implantation of smart factories with concepts of Industry 4.0 (I 4.0). On the other hand, new technologies do tend to solve difficulties faced by maintenance teams by building a history of failure analysis that, in the long or medium term, presents a positive result. This becomes more complicated with

complex equipment, such as the spindle, a component of a machine tool, whose complexity is detailed in the studies of Sadasivam, Archenti and Sandberget (2018), Abele, Altintas and Brecher (2010) and Mosyurchak, Veselkov, Turygin and Hammer (2017). According to these authors, it is necessary to develop methodologies for identifying flaws and coherent action plans so that the maximum life of the equipment is reached to ensure smooth progress from production to delivery to the final customers.

Knowing this scenario and the analysis of traditional failures in industrial maintenance processes, online monitoring of equipment using Internet of Things (IoT), Cloud Computing and Big data technologies has emerged as an alternative. Liao, Loures and Deschamps (2018) state that the integration of such technologies in industrial processes will promote a change in production systems and that predictive maintenance will benefit from the volume of data acquired systematically to solve critical problems. Having sensor on the spindle sending data to a system capable of storing data online is only possible with the use of cloud computing, responsible for storing the data on a network in which the sensor will deposit the data collected. In addition, working with this information through big data is essential to know the normal behavior of the equipment and thus establish new models of failure monitoring.

In this sense, the literature points to attempts to develop models for online monitoring of spindles with the objective of knowing the normal working conditions and thus checking which new actions could be established in order to eliminate the existing stops in production. Online monitoring of spindles presents several difficulties, namely the variation of spindle rotation and tool models. Due to these difficulties, Holub and Hammer (2017) present a model that directs the monitoring to be carried out in a vacuum, that is, without a tool. Rastegari, Archenti and Mobinet (2017) suggest more studies to understand the behavior of the spindle when monitored at different rotations, which in fact suggests a gap in studies.

Given this gap, this research aims to evaluate the online monitoring of spindles in a woodworking machine tool. To this end, a case study was conducted in an industry in the furniture sector. The research question now investigated is: *how can an online spindle monitoring system be applied and what benefits are offered for the maintenance process?* For practical results, it was noticed that the use of online monitoring increased facilities in the control of maintenance operations, as well as reduced operating costs for the organization. The theoretical contributions of this study include the review of authors dealing with the topic, as well as the possibility of this study influencing new research in the field of the

furniture industry, as well as the application of monitoring technologies in machine tools in the metalworking industry.

2. THEORETICAL BACKGROUND

Machine tools have constantly evolved throughout history, combining new technologies that increasingly add knowledge to the entire production system. In this sense, Sadasivam, Archenti and Sandberget (2018) understand that a machine tool is complex with several mechanical, electronic components and subsystems. To differentiate the evolution over time, Xu (2017) presents how Machine Tools 4.0 should be, indicating them as necessary assets for the implantation of intelligent factories in the machining industry.

The characteristics of machine tools in each of the industrial revolutions are presented by Xu (2017), and the so-called Machine Tool 1.0, which was established during the first industrial revolution, had a mechanical drive and was operated manually. In Machine Tool 2.0, which appears in the second industrial revolution, the numerical command already appears in the machines. During the third revolution, which is currently being finalized, the Machine Tool 3.0 is known for modern computer numerical commands (CNC). Finally, coming from the technologies of I 4.0, Machine Tool 4.0, which Xu (2017) defines as one of the pillars of cyber-physical systems such as IoT and cloud computer, plays a fundamental role in the development of new studies.

This evolution of this concept in recent years was only possible due to the several advances around the so-called I 4.0, also known as the Fourth Industrial Revolution (Cañizares and Valero 2018). Sadasivam, Archenti and Sandberget (2018) mention that several transformations are happening rapidly in factories, making them more intelligent as a result of initiatives such as “Produktion2030” from Sweden, “ Industries 4.0”; from Germany, “Factory 2050” from UK, “Horizon2020 ” from the European Union, “ Revitalize Manufacturing Plan ” from the United States of America and “ 4th Science and technology plan ” technology from Japan. Mourtzis, Milas and Athinaios (2018), include initiatives such as that of China, called “Made in China 2025” and the European industry called “Factories of the Future”. All of these initiatives further fuel the need to publicize Brazilian initiatives for the implementation of such technologies in the national territory.

In order to conceptualize what I 4.0 is, Nagy, Olah, Erdei, Mate and Popp (2018) mention that it is the quest to develop new means of automation combined with operational efficiency

and effectiveness. Additionally, Oztemel and Gursev (2020) indicate in their literature review that the I 4.0 encourages the implementation of technologies more personal and agile in production through its manufacturing philosophy. For this, it is necessary to include enabling technologies from I 4.0, such as Cyber-Physical Systems (CPS), Internet of Things (IoT), Internet of Services (IoS), Robotics, Big Data, Cloud Computing and Augmented Reality. All of these technologies allow the integration of different interfaces, machines, and devices that will be able to provide and collect data to make any environment more intelligent. In order to validate this concept, it is also important to understand how those responsible in companies for the necessary investments for the implementation of technologies understand I 4.0.

All are moving in the same direction of using network data to understand the behavior of machines, making it possible to make decisions quickly or even to make predictions based on online data. Mosyurchak, Veselkov, Turygin and Hammer (2017) understand this fact as digitalization, in which we will have several machines connected in a cyber-physical system generating data that will be shared in a network environment at all levels. Nagy, Olah, Erdei, Mate and Popp (2018) consider that for a factory to be totally intelligent, it is necessary that the entire plant, not just a product line, remains digitally connected.

Thus, it is important to analyze which components of a machine tool can be monitored for data collection, and consequently, the availability for assertive decision making. Thus, one of the main components of a machine tool is known as the spindle, which, according to Abele, Altintas and Brecher (2010), is an extremely complex component and responsible for the following functions: a) rotating tools (milling machines, drills, grinding wheels, among others) or work pieces with precision and, b) transmitting the necessary energy to the cutting area of the metal.

To Sadasivam, Archenti and Sandberget (2018), the spindle is a highly precise system composed of several components that perform their functions within the pre-established limits for their work capacity. Mosyurchak, Veselkov, Turygin and Hammer (2017) mention that the spindle is one of the critical items of any machine tool, and the costs involved in its maintenance cannot be neglected. Ziada, Yang and DeGroat-Ives (2017) explain that obtaining data from the inside of a spindle is extremely complex and occurs only with its disassembly of the set or with the support of manufacturers.

Figure 1 illustrates a motorized spindle in a cross section to visualize the main components, which are: Ceramic Bearings, Front and Rear Housing, Stator, Spacer, Shaft, Encoder, Finger Assembly System, Rotor, Draw Bar and Front Shaft Nut.

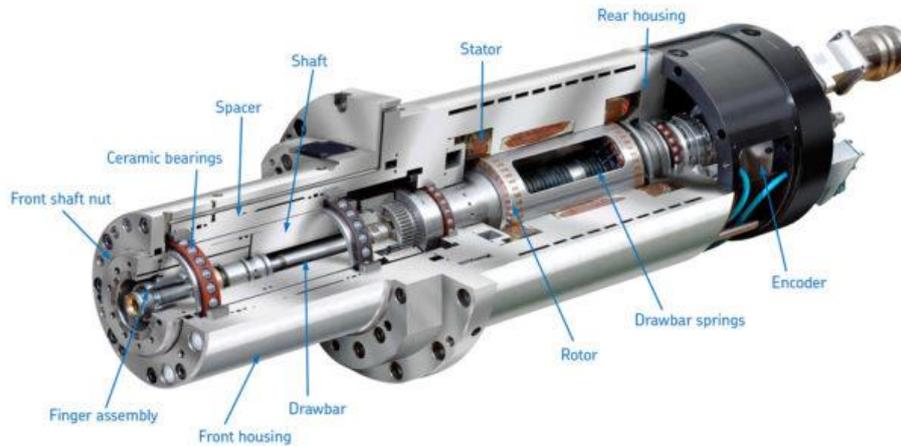


Figure 1: Main components of the spindle

Source: <https://www.fabricatingandmetalworking.com/2019/01/prescription-for-machine-tool-heart-failure>

The spindle will need to fit the needs of I 4.0 or Machine Tools 4.0, as proposed by Xu (2017). With this objective, Cao, Zhang and Chenet (2017) developed the concept of the intelligent spindle, which can be described as a spindle with sensitive capabilities, decision making, and control, all of which guarantee the best condition in the machining process and reliable operations. The evolution presented by Cao, Zhang and Chenet (2017) is fundamental for the evolution of spindles and machine tools. However, it is something expected for future development, as it will be necessary for a new project to foresee all sensing, intelligent actuators, and real-time data processing with decision making through algorithms.

However, the current moment should be analyzed since this new, more advanced spindle is a distant reality in companies that have machine tools in Brazil. Companies invest little in monitoring the condition of the spindle because they consider this equipment with relatively high durability and focus on preventive and corrective maintenance, which might be minimized in the implementation of the fourth industrial revolution. From the point of view of Gopalakrishnan, Skoogh, Salonen and Aspet (2019), preventive maintenance must be planned for the criticality of the equipment while corrective maintenance occurs exactly when an unexpected event occurs. As a result of these models currently adopted, once a defect in the spindle is presented, there is no time to make a decision to stop the machine or fix it because any failure in the spindle generates high losses, both during repair and when the line is stopped of production.

Regarding the machine stop, another relevant point brought by Gopalakrishnan, Skoogh, Salonen and Aspet (2019) is that, currently, the way in which decisions about what type of maintenance to apply results in several activities that do not add value to the process, thus reducing machine availability. Regarding the need for repair, Janak, Stetina, Fiala and Hadas (2016) mention that despite the years, preventive and corrective maintenance on machine tools still applies; however, the authors point out that new technologies will be used for the development of condition-based maintenance and, machine tools can be equipped with the most varied sensors.

In this sense, the work presented by Cao, Zhang and Chenet (2017) is extremely relevant for the future development of spindle projects, and they also mention the interest in maintenance by prognosis or based on the condition. Prognostic maintenance on spindles or any other equipment is based on the concept of predictive maintenance. Lee, Kim, Quan, Kim, Kim, Yooh et al. (2018) show that the prognosis is used to calculate and predict the future condition of the component, bringing an idea of the remaining useful life that will assist in decision making. For Lee, Kao and Yang (2014), condition-based maintenance deals with the acquisition and analysis of data to perform machine monitoring. This information will serve as a basis for the maintenance team to carry out only the interventions that are really necessary and, in this way, reduce the waste arising from unnecessary stops. Sadasivam, Archenti and Sandberget (2018) reinforce the description of condition-based maintenance and add that the evaluation of the machine integrity is carried out continuously and in different ways with the intention of identifying wear variations and consequently preventing failures. Li, Wang and Wang (2017) emphasize that any predictive maintenance has the main objective of reducing downtime and the cost related to the maintenance of the asset as well as predicting any failure that may occur.

Roy, Stark, Tracht, Takata, and Mori (2016) mention that continuous maintenance is an engineering service that seeks the highest performance and the lowest cost during the life of the machine. To do this, they list the six key areas to reach this level: mechanisms of degradation and service, repair, monitoring, diagnosis and prognosis, autonomous maintenance, and obsolescence. Other similar concepts are PHM (Prognostic and Health Management) found in Liu and Xu (2017), Machine Healthy Management discussed by Lee, Kim, Quan, Kim, Kim, Yooh et al. (2018), Machine Healthy presented by Lee, Kao and Yang (2014) and SMTS (Smart Machine Tool Systems) discussed by Jeon, Yoon, Um and Suh (2020) which presented an architecture seeking to avoid machine failure and zero defect.

Considering that companies in this sector of woodworking machine tools use few predictive maintenance systems, the use of prognostic maintenance or condition-based maintenance is currently a challenge because if the normal condition of the spindle during an empty test for offline vibration data collection is not known, then its operation with online monitoring as referenced by Mosyurchak, Veselkov, Turygin and Hammer (2017) is also unknown. These authors believe that it is important to differentiate between the types of collections performed for later determination of failures. Although Holub and Hammer (2017) propose an online monitoring system in which the collection of vibration data must occur in an empty operation to record more reliable data, the difficulty of this analysis is also demonstrated by Rastegari, Archenti and Mobinet (2017) proving further studies are indispensable due to the high variation in speed during the machining process.

Ziada, Yang and DeGroat-Ives (2017) corroborate the use of online systems on the shop floor to obtain online data for analysis in addition to the use for machining process control. They also reinforce the need to know the frequency of failure of the spindles well, as they will hardly have details of the project unless it is made available by its manufacturer. Lee, Wu, Zhao, Ghaffari, Liao and Siegel (2014) discuss the creation of fault models through online monitoring but without machining load. That is, it is necessary that within the program, a few seconds are foreseen for the data to be collected for analysis in order to define the probability of failure. The model is extremely valid, but the evolution of the analysis of vibration data with online collection in machining periods is inevitable because, in this way, the real operating conditions can be known, in addition to being able to identify possible flaws not yet studied and still gain time in the production process.

In order to be able to analyze failure probabilities based on real-time information, it is essential that the data collected through devices with IoT technology are allied to the data digitization process. According to Gopalakrishnan, Skoogh, Salonen and Aspet (2019), a digitized factory creates opportunities in terms of information quality, which is obtained through the IoT and/or digital tools. In fact, the support of new technologies allows for obtaining data in real time. One of the main reasons for the digitization event is the IoT. For Nagy, Olah, Erdei, Mate and Popp (2018), IoT devices are technological instruments capable of acquiring different types of information to share them on a corporate network or between companies. They mention cameras and / or 3D scanners capable of transmitting the condition of what is being observed as well as sensors such as RFIDs (Radio-Frequency Identification),

which are tags placed on products that transmit information about their storage location or other desired features. Liao, Loures and Deschamps (2018) describe the information network created by different IoT devices within a company in order to follow the cycle of products or processes and can be called Industrial Internet of Things or IIoT. Civerchia, Bocchino, Salvadori, Rossi, Maggiani and Petracca (2017) cite that IIoT can be used to create effective smart factories, in which each sensor will be considered a device for detecting real data. In this condition, system operation patterns can be defined and when there are variations, a new level of analysis is identified. Chui, Löffler and Roberts (2010), on the other hand, understand that this new environment for relating different data will provide the possibility to create new business models, improving processes with a reduction in costs and risks involved.

In order to extend the life of spindles, it is understood that, as mentioned by Lee, Ni, Djurdjanovic, Qiu and Liao (2006), when intelligent machines are monitored and connected to each other, with their data being modeled and analyzed remotely, it will be possible to advance in obtaining an intelligent prognosis, in addition to good predictive maintenance. However, it is necessary to start the installation of sensors in suitable locations and data in a continuous production environment that allows obtaining this data to create a failure analysis model. Ben-Daya, Hassini and Bahroun (2017) ponder exactly this question for future study: what is the best place for positioning the sensor and how to identify possible alarm levels in order to create a communication logic? This is one of the points that is targeted in the approach throughout the study focused on the maintenance of spindles.

3. RESEARCH METHODOLOGY

This research has a qualitative approach of a theoretical and empirical nature with a descriptive objective, through the application of the case study method (Yin 2014), using bibliographic research and observation during the research development process as data collection technique. Bibliographic research was carried out, and after that, a case study was carried out in the furniture industry in order to evaluate how the online monitoring of spindles works and what benefits are offered to the maintenance process.

The review of the literature was carried out based on the assumptions of Alcantara and Martens (2019) and the main keywords defined for research on scientific databases in the academic community and followed by content analysis. As for keywords, combinations of terms were used, highlighted in Table 1.

Table 1
Keyword research structure

Keywords	Scopus	Web of Science	Science Direct	Emerald Insight	Scielo
Machine Tools	1	2	2	0	0
Machine Tools + Powertrain	0	0	0	0	0
Machine Tools + Powertrain + Spindle	0	0	0	0	0
Machine Tools + Industry 4.0	13	1	3	0	0
Machine Tools + Industry 4.0 + Maintenance	38	15	7	1	0
Machine Tools + Industry 4.0 + Maintenance + Spindles	1	1	2	0	0
Machining Center + spindle + Industry 4.0	4	2	2	0	0
Machine Tools + Industry 4.0 + Internet of things	12	2	0	0	0
TOTAL	69	23	16	1	0

With the keywords defined, searches were carried out on the scientific databases Web of Science, Scopus, ScienceDirect, Scielo and Emerald Insight to identify the volume of articles related to the theme. This research provided 109 selected articles using a search period starting in 2006. The articles were selected by checking the title, abstract, and keywords for articles related to predictive maintenance using vibration data as a diagnostic on machines. From this selection, the basis of the theoretical background was extracted, and from the inputs of the main authors of the sample, the theoretical model was developed and used in order to determine the protocol for the case study.

The case study, which according to Yin (2014), deals with an empirical investigation with the objective of analyzing a contemporary and real event but with the need to advance in the knowledge of this event. This study is considered a single case study, which for Yin (2014), can give new directions for future work in addition to contributing to the construction of the theory and base knowledge.

For the development of this case study and convenience, a partnership was made between the company that owns the machine tools and the company responsible for the maintenance of the spindles. The company that owns the machine tools is one of the largest furniture manufacturers located in south of Brazil.

Data collection was performed through a failure analysis of a spindle during the disassembly process and through the online monitoring system that remains collecting data during the spindle operation in the woodworking machine tool process. These follow-ups took place during the period from January 2018 to September 2019.

The data were treated and analyzed using the content analysis technique based on Bardin (1977). According to the author, content analysis encompasses systematization as well as explanation and expression of the content of messages in analysis categories. The content analysis took place through analysis of process documents, online routines in the monitoring system, and semi-structured interviews applied in meetings with managers, suppliers and operators of the company targeted by the case study, with the team responsible for monitoring: Reliability Engineer; Service Engineer; Business Consultant; Service Coordinator; Maintenance Coordinator and Maintenance Technician.

4. ANALYSIS OF THE RESULTS

4.1. Description of the target company of the study

The company targeted by the case study is one of the largest and most modern planned furniture manufacturers with an industrial park of more than 50 thousand square meters, located in the furniture hub of south of Brazil, in the state of Rio Grande do Sul. With nearly 30 years of experience in the furniture segment, it has the capacity to produce more than 180,000 modules per month and has a vast network of authorized resellers serving the different furniture market niches. It has a just-in-time production system in addition to highly technological production lines in which their machines allow a high level of productivity and variety of items that is part of the furniture market.

For the purpose of identification and differentiation of the name used by the company, we will adopt the name of WM to refer to the machine on which the studies related to this article were carried out. The company has two WM machines, each of which has six spindles working simultaneously, with two spindles being responsible for the longitudinal cutting of the wooden sheets and the remaining four spindles are responsible for the transversal cuts. Figure 2 shows the WM in a plan view in which it is possible to observe the arrangement of each spindle, identified as S1, S2, S3, S4, S5 and S6. The arrows E identify the entrance of the wooden sheets, and the arrow S identifies the exit of the cut material according to the dimensions established in the final customer project. In Figure 2, the dimension of the machine can be seen through Photo (b) with the same signs used in Photo (a).

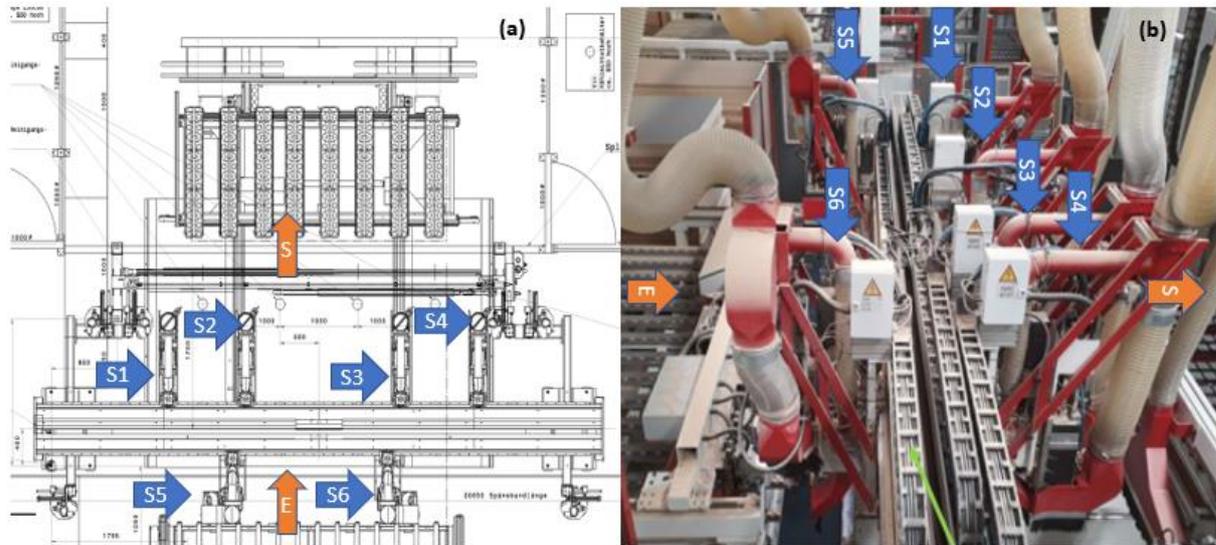


Figure 2: Plan view of the WM machine

Source: adapted by the authors based on the case study

It is important to mention that the machine has an automated system for project identification, in which each process will receive different sizes of wooden sheet, and consequently, there will be different final sizes of cut sheet for the final formation of the planned furniture developed by stores in major centers. Because WMs are strategically positioned within the company, they determine the production flow of the other edge banding machines, double end tenoners, and other processes. This means that any stop at one of the spindles of one of the WMs, the production flow will be interrupted, translating to a loss of 50% of production for the entire company, causing delays to the end customers. That is, it is a bottleneck and critical process for the maintenance team.

The spindles of these machines are from the manufacturer Omlat model 065352, dedicated to woodworking machines tools with a working speed of 22,000 rpm (revolutions per minute). It consists of four angular contact bearings with ceramic balls, lubricating grease, and sealant to prevent the entry of wood dust from the machining process. In addition, this spindle has a tool clamping system for an HSK 50 cone with exchange monitored by internal sensors. Furthermore, it is driven by a motor integrated into the spindle, conceptualizing it as a motorized spindle. It also has an internal cooling system to control the vibration temperature.

The objective of this research was to evaluate the online monitoring of spindles in woodworking machine tools. Even though the WM has more sensors, the analysis was done

through the online vibration monitoring process, resulting from the constant failures in the S5 and S6 positions of the WM machines. However, to understand how this model was chosen, the maintenance process will be detailed until the implementation of online monitoring.

4.2. Detailing of the maintenance system

For WM machines, the target company of the case study uses the preventive maintenance system combined with monthly vibration collections with an offline monitoring system. In this way, by means of a pre-established schedule, the contracted company performs data collection, downloads this data in appropriate software for analysis, performs this analysis and later presents a technical report on the defects or probable failures that would occur based on this analysis.

A major problem with this process is that the measurement was performed in one day, and the analysis could be delivered in up to 5 days. Under this scenario, the problem reported 5 days after the measurement could no longer correspond to the current condition of the machine because during this period about 120 hours of production were fulfilled, and a series of events may have occurred without any record for maintenance.

Another point of attention is about the attachment of the sensor. The housing of this spindle is made of aluminum and a magnetic base that is usually used to attach sensors for offline monitoring. Therefore, for the collection in this spindle, the technician would need to hold the sensor with his own hands in the region where the bearings are mounted. In addition to the inadequate security condition, the quality of data collection was also lost, directly influencing the reliability of the data for analysis.

The large measurement range can be explained by the specific characteristics in this machining process in which the spindles went into catastrophic failure; that is, the spindles braked during the production process without any prior notice to the maintenance team. Obviously, the disturbance generated was immense, considering the importance of WMs in the company's production process.

A catastrophic failure in any equipment will always increase the maintenance cost due to the greater number of damaged components to restore the normal operating condition. Another interesting point that was observed is that traditional industrial engine maintenance companies were used instead of using companies specialized in the maintenance of high-speed spindles.

Figure 3 shows the number of components damaged in a catastrophic failure of this spindle in the WM machine. In Photo (a), we can see the main shaft bearing seat damaged due to a

crash. Photo (b) shows the broken nut, and Photo (c) identifies the spindle housing, that is, the box where the bearing is mounted completely outside the dimension required for the perfect functioning of the spindle. Photo (d) represents a cracked closing cover, and Photo (e) shows the wear on the bearing mounting adjustment pad. Finally, Photo (f) identifies the bearing still in the spindle housing with the crash characteristics and consequently generating the damage reported in the other items.

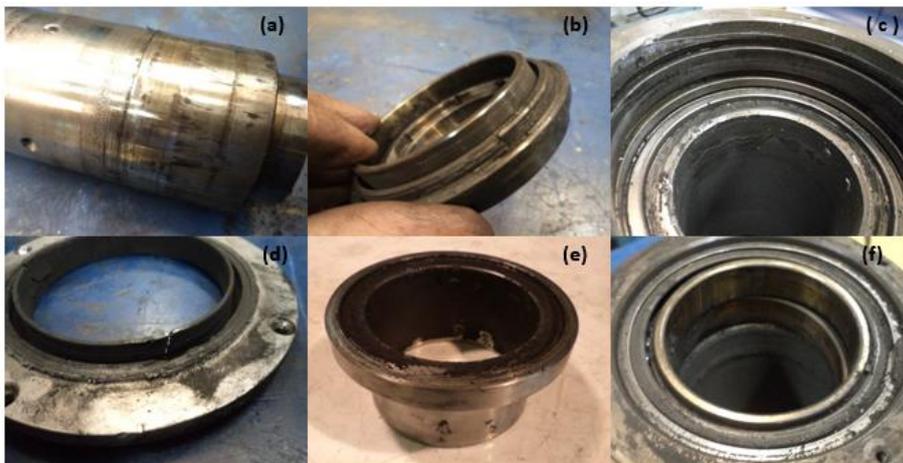


Figure 3: Damaged spindle components

Source: adapted by the authors based on the case study

After the spindle maintenance process, it returns to the company and can stay in stock or go into operation immediately. As the company has spare spindles, this item would normally go into inventory. However, during the beginning of this study, recurrent failures did not allow such an action. With the development of this scenario, it was decided to proceed with online vibration monitoring.

4.3. Online monitoring process

The online vibration monitoring process basically consists of collecting vibration data in real time with the objective of providing information for the maintenance team to act on time and avoid catastrophic failures as reported in topic 4.2.

The service and systems supplier, SKF Brazil, has a spindle maintenance service area and a complete portfolio of online and offline condition monitoring systems. It also has an asset management center, known as the REP Center (Rotating Equipment Performance Center), which is responsible for monitoring more than 736,000 rotating equipment and more

than 2.2 million bearings across America. This structure was used to implement the concept of online monitoring in spindles, which was not developed in this model until then. This partnership developed control the maintenance of the spindles during the critical moment of failures in the company through its service unit located in the city of Sao Paulo.

The online monitoring system consists of a module called IMx-8, cables, and vibration analysis sensors. The data is collected during the machining process and transmitted to a cloud-hosted software (Cloud Computing), called @ptitude analyst. In this software, it is possible to carry out vibration analysis, monitor failure trends, and present diagnostics. The diagnostics granted in the software are automatically transferred to a web dashboard known as Machine Healthy Viewer, responsible for demonstrating to the customer the history of events of its spindle. Subsequently, engineering actions may be taken according to the failure history acquired during the condition management process. The composition of the entire WM online monitoring system was based on the model of the REP center, and through the following activities detailed in five stages.

First step: Attach the sensors to the WM Spindles S5 and S6. For reliable collection, it is necessary to fix the sensors in a position close to the bearing assembly region. For this, a front point (2) and a rear point (1) were defined according to Figure 4. Photo (a) shows the position of the two sensors and Photo (b) shows a highlighted photo of the position of the sensor in the front region of the spindle.

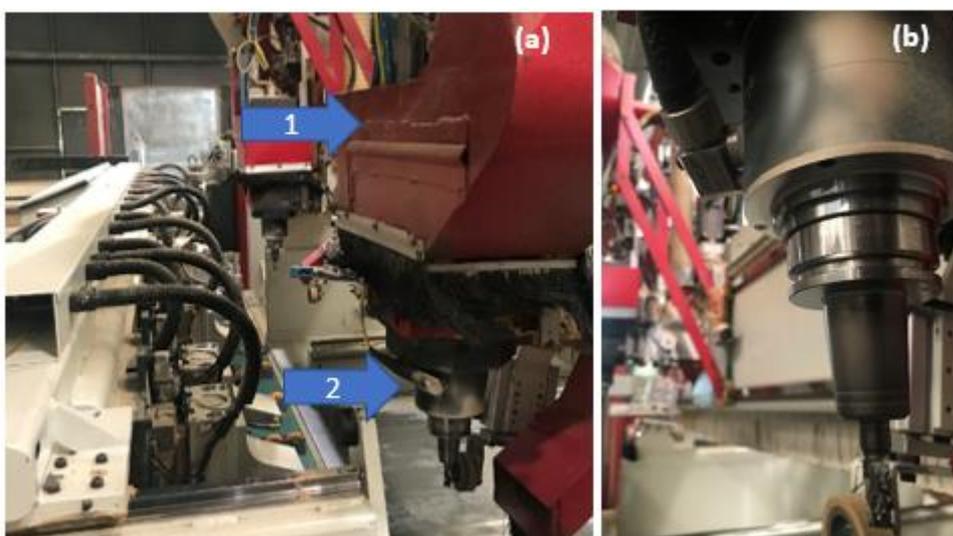


Figure 4: Positioning the sensor and IMx-8

Source: adapted by the authors based on the case study

Second step: Run the cables from the sensors to the IMx-8 hardware. For the connection between the sensors and the IMx-8 module, dedicated cables were used for this application and distributed from the spindles to the machine panel, as shown in Figure 5 Photo (a).

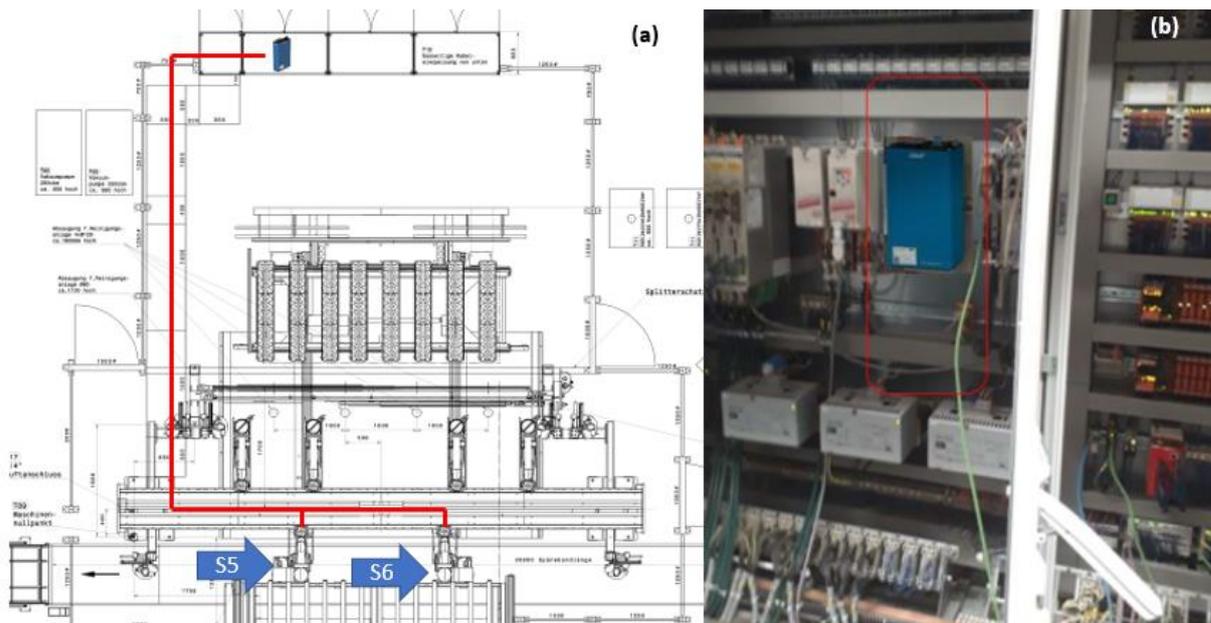


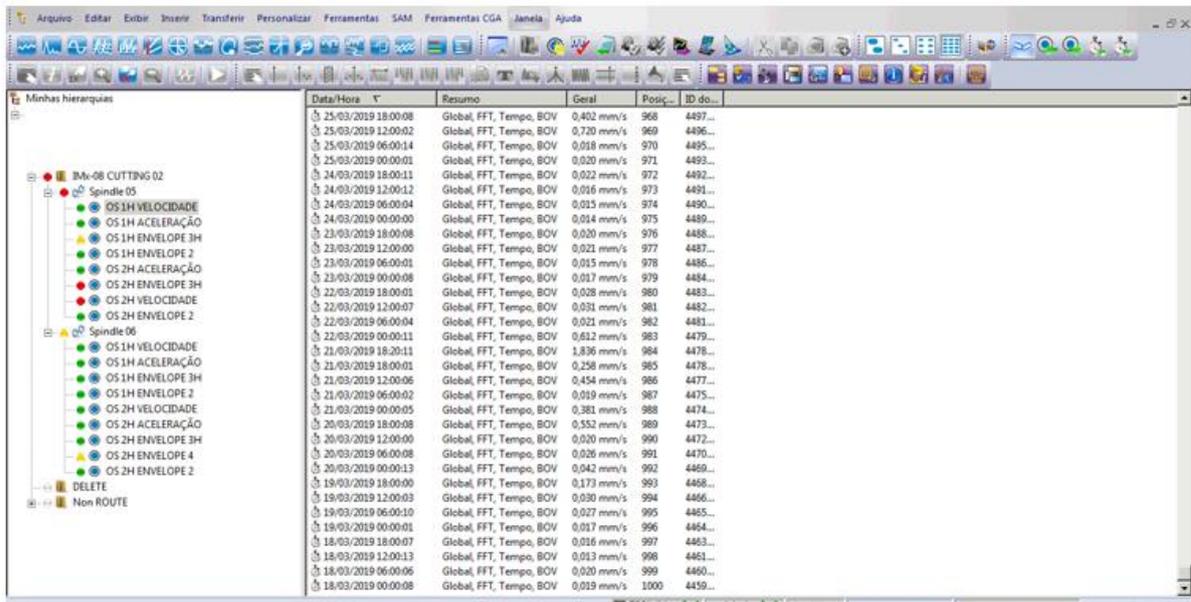
Figure 5: Sensor cable layout

Source: Adapted by the authors

Third step: Mount the IMx-8 hardware on the machine's electrical panel. This activity consisted of properly positioning the IMx-8 on the machine's electrical panel in addition to assembling the sensor cables in the appropriate terminals, electrical power connection, and the communication cable with the network for communication with the cloud. Figure 4, Photo (b) shows the positioning of the module in the electrical panel of the WM machine.

Fourth stage: Provide an IP for communication with the cloud and configuration of points in the software *@aptitude analyst*. The company should provide the IP address for configuring the module with the cloud. In this way, it is possible to perform the setup steps after configuring the points in the software *@aptitude analyst*. The configuration of the points in the software is based on the three basic vibration analysis techniques, known as Speed and Acceleration as used by Rastegari, Archenti and Mobinet (2017) in addition to the Envelope technique present in the software. With that, the points were left with the structure and hierarchy in the software represented by Figure 6. As can be seen in Figure 6, below spindles

05 and 06, there are the rear points called OS 1H followed by measurement, speed, acceleration and envelope techniques. For the Envelope, specific filters can be applied for a better vibration analysis. In this case, the dots are labeled Envelope 3H, Envelope 2, or Envelope 4.



Data/Hora	Resumo	Geral	Posic.	ID do...
25/03/2019 18:00:08	Global, FFT, Tempo, BOV	0,402 mm/s	968	4497...
25/03/2019 12:00:02	Global, FFT, Tempo, BOV	0,720 mm/s	969	4496...
25/03/2019 06:00:14	Global, FFT, Tempo, BOV	0,018 mm/s	970	4495...
25/03/2019 00:00:01	Global, FFT, Tempo, BOV	0,020 mm/s	971	4493...
24/03/2019 18:00:11	Global, FFT, Tempo, BOV	0,022 mm/s	972	4492...
24/03/2019 12:00:12	Global, FFT, Tempo, BOV	0,016 mm/s	973	4491...
24/03/2019 06:00:04	Global, FFT, Tempo, BOV	0,035 mm/s	974	4490...
24/03/2019 00:00:00	Global, FFT, Tempo, BOV	0,014 mm/s	975	4489...
23/03/2019 18:00:08	Global, FFT, Tempo, BOV	0,020 mm/s	976	4488...
23/03/2019 12:00:00	Global, FFT, Tempo, BOV	0,021 mm/s	977	4487...
23/03/2019 06:00:01	Global, FFT, Tempo, BOV	0,015 mm/s	978	4486...
23/03/2019 00:00:08	Global, FFT, Tempo, BOV	0,017 mm/s	979	4484...
22/03/2019 18:00:01	Global, FFT, Tempo, BOV	0,028 mm/s	980	4483...
22/03/2019 12:00:07	Global, FFT, Tempo, BOV	0,031 mm/s	981	4482...
22/03/2019 06:00:04	Global, FFT, Tempo, BOV	0,021 mm/s	982	4481...
22/03/2019 00:00:11	Global, FFT, Tempo, BOV	0,612 mm/s	983	4479...
21/03/2019 18:20:11	Global, FFT, Tempo, BOV	1,836 mm/s	984	4478...
21/03/2019 18:00:01	Global, FFT, Tempo, BOV	0,258 mm/s	985	4478...
21/03/2019 12:00:06	Global, FFT, Tempo, BOV	0,454 mm/s	986	4477...
21/03/2019 06:00:02	Global, FFT, Tempo, BOV	0,019 mm/s	987	4475...
21/03/2019 00:00:05	Global, FFT, Tempo, BOV	0,381 mm/s	988	4474...
20/03/2019 18:00:08	Global, FFT, Tempo, BOV	0,552 mm/s	989	4473...
20/03/2019 12:00:00	Global, FFT, Tempo, BOV	0,030 mm/s	990	4472...
20/03/2019 06:00:08	Global, FFT, Tempo, BOV	0,026 mm/s	991	4470...
20/03/2019 00:00:13	Global, FFT, Tempo, BOV	0,042 mm/s	992	4469...
19/03/2019 18:00:00	Global, FFT, Tempo, BOV	0,173 mm/s	993	4468...
19/03/2019 12:00:03	Global, FFT, Tempo, BOV	0,030 mm/s	994	4466...
19/03/2019 06:00:10	Global, FFT, Tempo, BOV	0,027 mm/s	995	4465...
19/03/2019 00:00:01	Global, FFT, Tempo, BOV	0,017 mm/s	996	4464...
18/03/2019 18:00:07	Global, FFT, Tempo, BOV	0,016 mm/s	997	4463...
18/03/2019 12:00:13	Global, FFT, Tempo, BOV	0,013 mm/s	998	4461...
18/03/2019 06:00:06	Global, FFT, Tempo, BOV	0,020 mm/s	999	4460...
18/03/2019 00:00:08	Global, FFT, Tempo, BOV	0,019 mm/s	1000	4459...

Figure 6: Confirmation of collection by date and time in the software

Source: adapted by the authors based on the case study

Fifth step: Confirm collections being transferred to the software. After all the configuration, the process of collecting and confirming whether the data is being uploaded to the cloud begins. This confirmation is done by verifying the data record by the software as shown in Figure 10, which indicates the day and time of collection.

After completing the five steps, the system is ready to collect and store the data in the software. The vibration analysis will be performed remotely, and the diagnostics will be made available on the Machine Healthy Viewer so that the maintenance team of the owner of WM can monitor the condition of the spindles.

4.4. Evaluation and discussion of the benefits of online spindle monitoring model

With the IoT online spindle monitoring system operating in the organization and being analyzed from January 2018 to December 2019, it was possible to identify the benefits of the spindle maintenance management model using online monitoring and remote information analysis.

It is noticed that the *Higher frequency measurement history increases data reliability* through the online monitoring system given by an IoT device that allows for the collection of different information, depending on the characteristic of the sensor, as mentioned by Nagy, Olah, Erdei, Mate and Popp (2018). Thus, it is possible to acquire a quantity of data collections infinitely higher than offline monitoring when compared by Holub and Hammer (2017), who compare the types of measurement to understand the possible differences between the measurement methods. For example, the system could record a collection every two seconds. Obviously, care must be taken with the amount of data stored and how much it will assist in decision making.

In the previous process not using online monitoring, a measurement was recorded every six hours. As is the standard established for this company, there will be 4 daily collections and a total of 120 collections in the month, that is, there was a data collection per month to analyze. With a larger volume of data, it is possible to increase the reliability of decision making due to the repeatability of the measurement. Another point that must be considered is that the data collection, which carried out in operation, with machining load and identifies any anomaly, is used to understand the normal behavior of the machine, which is the next listed benefit of the research. Rastegari, Archenti and Mobinet (2017) present the vibration variations in different speed ranges, confirming the need to know the normal condition of the spindle, in addition, Liu, Vengayil, Zhong, and Xu (2018), thinking of a fully connected factory, indicate that it is essential to obtain data in real time, that is, repeat measurements so that when a fault occurs, it can be identified in the shortest possible time.

Knowing the normal behavior of the machine during cutting operation is one of the great challenges and with the system in place in this case study, it was possible to experiment with a working model based on the natural collection of the online monitoring system. It is possible to exemplify through the trend graph of Spindle 5 at the rear point OS 1H Envelope 3H, shown in Figure 7, Photo (a). Analyzing the trend graph, it appears that the first green quadrant was considered within the normal working conditions of the spindle. In a second step, we have an increase in the levels of vibration at this point, which remains for an approximate period of one month. At this point, the replacement of the spindle was suggested, and in the third green quadrant, the spindle condition returns to the condition considered normal.



Figure 7: Variation of normal spindle behavior and in the Process

Source: adapted by the authors based on the case study

The removal of the spindle was suggested based on the history acquired previously and for security of the working model developed among the companies; however, the following questions remain for future research: would it be possible to work a longer period with this spindle without a catastrophic event? Is it possible to relate the change in the normal behavior of the spindle with possible visible faults during the cartridge maintenance process? Rastegari, Archenti and Mobinet (2017) and Holub and Hammer (2017) warn against carrying out several tests in the most varied machining processes.

Concerning the *Identification of variations in the process* from the moment that the normal operating condition of the spindle is known, it is possible to assess the impact of variations in the process that were not previously perceived. It is evident in Figure 7, Photo (b), that there are two moments when the vibration condition is significantly changed and visualized in the OS 2H Speed front point. These points can indicate an event related to a collision or tool break or other type of impact that is generally not reported. This type of event may or may not generate failures in the spindle however, if this variation is identified, actions

can be taken by the maintenance team, and then everyone will understand what happens on the machine. Thus, it is important knowledge of the frequency of failure of each operation (Ziada, Yang and DeGroat-Ives 2017) in order to determine the correct time to remove the spindle from operation.

Concerning the *Possibility of obtaining information in real time* through the online monitoring system, it is possible to access the data remotely and check the behavior of the respective spindle in real time. With this access, the maintenance team can follow the situation of any event and make quick decisions to avoid failures that interrupt production, which corroborates the arguments of Gopalakrishnan, Skoogh, Salonen and Aspet (2019) about the need for quality information in real time.

The *Management data for visual management* through the online monitoring process, made available on Machine Health Viewer, facilitates the analysis of the data processed by the team of specialists for the management treatment. Therefore, the entire maintenance team will be aligned with the conditions presented in the WM machine, facilitating the predictive maintenance management of the spindles.

The *Possibility of fault identification* of the spindle before reaching catastrophic failures reduces maintenance costs (Figure 11). With the identification of the normal condition of the spindle, it is possible to work to avoid catastrophic damage. Lee, Ni, Djurdjanovic, Qiu and Liao (2006) understand the progress in making prognoses as vital, thus avoiding this type of failure. Only this action of real-time identification of possible failures represents a reduction in costs with the maintenance of the spindle, since a series of reworks will not be necessary. In addition, greater damage is avoided, making repair unnecessary and consequently reducing the need to purchase a new spindle.

Figure 8 shows the comparisons of percentage gains with the use of this online spindle monitoring methodology in addition to remote monitoring by specialists. It was noted that if a New Spindle (SN), represented in the first column, was acquired after a catastrophic break without possibility of repair, it has 100% of the financial value to be invested. In the next column, the percentage of the financial value of the Spindle Repaired after Catastrophic Failure (SRFC) is analyzed, which has a reduction of 79% in relation to the amount invested with an SN. That is, even if there is a catastrophic failure with the possibility of repair, the amount to be invested is 21% in relation to the SN, added to operational losses and machine downtime. In the third column, the Spindle Repaired after Online Monitoring (SRMO)

represents an additional 25% reduction compared to the SRFC value, and this is the most representative reduction for the company since maintenance is more common (SRFC) than the acquisition of new spindles (SN). In addition, we can analyse that the cost reduction is around 16% when compared with SN, added the short lead time between change the spindle.

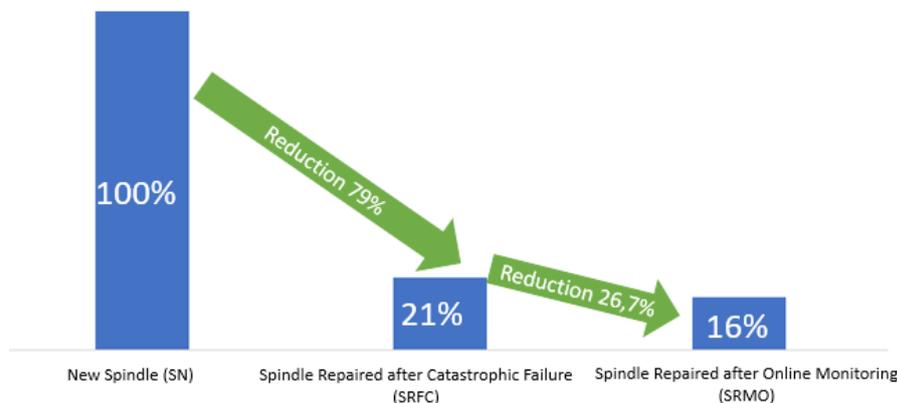


Figure 8: Maintenance Cost Reduction (% of financial value)

Source: prepared by the authors based on the case study

A second analysis carried out is related to the monthly maintenance cost, adopting the practice of predictive maintenance using online monitoring. In this case, Figure 9 shows the evolution of maintenance costs in the bar graph, in which it can be seen that in the first months of the system implementation, such as January 2018 and February 2018, there were costs of maintaining spindles to a degree limit of 100%, which was common for the team of the studied company until then. Beginning in March 2018, the maintenance cost becomes linear until the months of August, September and October 2018 in which there were occasional scope negotiations. From November 2018 until the end of the analysis of this research in December 2019, the cost becomes linear again. Thus, it is possible to affirm that, with the implementation of the online monitoring system analyzed, using IoT technology for online monitoring, coupled with the condition of maintenance of spindles, a reduction in maintenance costs was evidenced. In addition, a completely known predictability for the period of up to 15 months was seen, which is extremely important for maintenance managers.

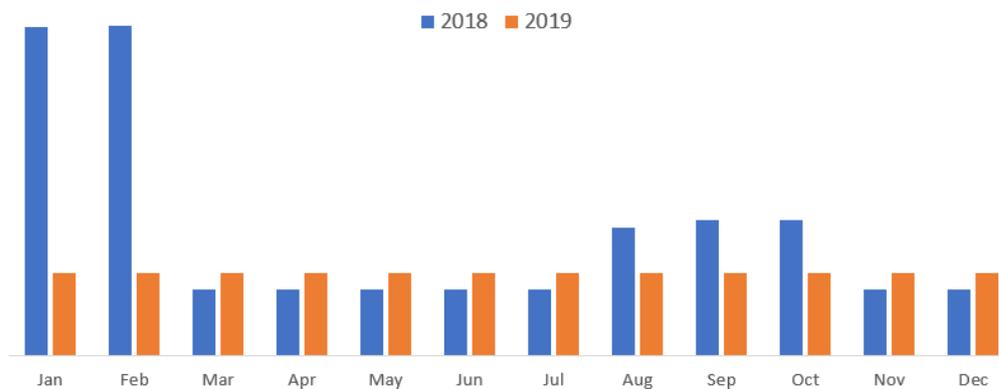


Figure 9: Monthly Cost Analysis of corrective maintenance for predictive

Source: adapted by the authors based on the case study

Regardless of not showing the absolute values of cost reduction for the privacy of the companies targeted in the case study and its service supplier, a cost reduction in any maintenance cost line is an extremely significant gain in the current competitive scenario. In addition, a new form of predictive maintenance was established in the company. The service provider company monitors the online monitoring system of the spindle and when an event occurs, information will be made available to the company via dashboards. If the replacement of the spindle is necessary, a message is sent directly to the person responsible for planning this activity. With the programmed stop, the replacement of the spindle is carried out by another one that is already available in stock, and consequently, the spindle that left the machine goes for repair. It is noticed that the machine downtime is planned and foreseen, and the time to replace the spindle is known, allowing the maintenance team continue reliably to the production. After the maintenance of the spindle, it returns to the company and will be waiting for the next replacement in stock.

With the analysis of the results of the case study, a change of culture is observed in the application of new concepts from I 4.0 and is discussed by Xu (2017) and Cañizares and Valero (2018). The digitization of vibration data, as discussed by Mosyurchak, Veselkov, Turygin and Hammer (2017) using IoT sensors for the collection of vibration are of paramount importance in the predictive maintenance process, and the technology mentioned by Nagy, Olah, Erdei, Mate and Popp (2018) , Liao, Loures and Deschamps (2018) and Civerchia, Bocchino, Salvadori, Rossi, Maggiani and Petracca (2017) in this work, allowed for the achievement of a new model of maintenance management of spindles in the furniture

company. Online spindle monitoring, as performed, using other methodologies given by Holub and Hammer (2017), Ziada, Yang and DeGroat-Ives (2017) and Rastegari, Archenti and Mobinet (2017) indicate an improvement in the spindle management process. The flow chart shown in Figure 10 details the steps for operation of the new model of spindles online monitoring in furniture industry.

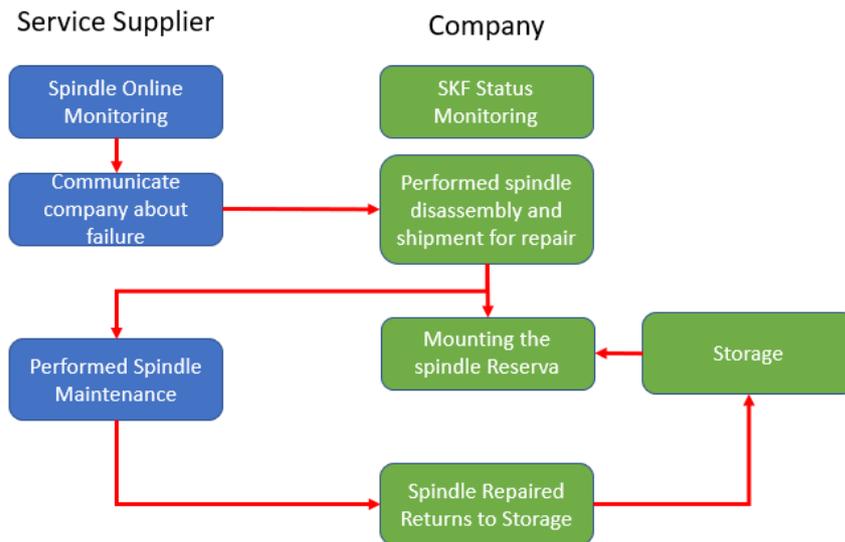


Figure 10: Steps for operation of the new model of spindles online monitoring in furniture industry

Source: adapted by the authors based on the case study

As argued by Gopalakrishnan, Skoogh, Salonen and Aspet (2019), the search for a new maintenance management model is essential to achieve new levels of excellence. In addition, providing the maintenance team with a higher level of management is essential to avoid unscheduled stops; for this reason, it is important to adapt the new technologies to the systems already in operation. Thus, the search for greater tests in real manufacturing environments with online monitoring, as well as the implementation of new models, must be constant.

5. FINAL CONSIDERATIONS

This article presented a case study with the objective of evaluating the online monitoring process of spindles in woodworking machine tools. It contributes to the possibility of managing the predictive maintenance of spindles through an online monitoring system, using the concepts from I 4.0, such as IoT and cloud computing, and acting in the gap of Holub and

Hammer (2017) and Rastegari, Archenti and Mobinet (2017), regarding spindle vibration problems.

In addition, making the processed data available through the digitalization of information collected via the IoT system in the manufacturing process and making such data available in a cash management dashboard facilitate the management of maintenance processes. Thus, this article can scientifically contribute through its evaluation of a new systematic of data collection and monitoring which had not been used in the wood industry until now and could possibly be scaled for other similar applications in the future. These results lead to extending the life of this equipment and thus, justifying the research question of how an online spindle monitoring system can be applied and what benefits are offered for the maintenance process, in this case in the furniture industry.

An important consideration is related to the practical contribution of cost reduction presented in the spindle maintenance process through technological advancement with online monitoring, given by IoT technology. To this end, there was a 25% reduction in the cost of repairing spindles, in addition to the cost of production and machine downtime, and which can be explored by practices in other applications, such as spindles online monitoring in machine tools for automotive parts.

The limitation of this study is related to not knowing the total cost of downtime to obtain greater gains from the application of online monitoring to expand the justification for using predictive maintenance, but thus, new studies and complementary research can highlight this point. Another limitation is related to the number of spindles monitored in this application. As mentioned, tests were performed on only two spindles out of a total of 12 spindles in operation in the organization studied. It is important to highlight that this case study evaluated the first woodworking machine tool in Brazil to test the online monitoring of the vibration parameter in spindles. In this way, it is possible, in a future work, to measure the gains obtained with the online monitoring of the entire operation, in addition to modeling and use of artificial intelligence to self-control the process.

In addition to this future work, it is essential to carry out tests of this model in other factory environments, mainly in the automotive industry, in which there is a high number of machine tools operating and which probably need models similar to this one in order to increase production processes and predictive maintenance as well as maximize profitability of manufacturing processes.

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