Towards effective maintenance of overhead conveyor systems: a case study in an automotive industry

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Abstract: The current industrial contexts make sustainability requirements ubiquitous, pushing automotive industries to reach new sustainability targets for a competitive production. In the automotive industries, the material handling system (MHS) is widely recognized as a critical component of the production system, due to its highly automated operation, which requires efficient maintenance activities. However, maintenance processes often are not effective becoming responsible of several problems, such as the plant unavailability, the increasing of production and maintenance costs, unexpected failures, greater material and energy consumption, as well as possible defective products. Nevertheless, no case study providing the implementation of effective maintenance strategies on MHSs was found in the literature. For these reasons, the paper presents a case study showing the effective process for the implementation of Condition Based Maintenance (CBM) on an MHS of an automotive European company. The MHS is characterized by a belt-driven and motorized roller conveyor used for the horizontal transfer of carriers, on which several body elements are positioned. First, the system analysis and the identification of the critical components based on the application of the Failure Mode, Effect, and Critically Analysis (FMECA) was performed. Then, for each critical component, the measurable parameters to be monitored and the intervention thresholds to apply an effective CBM, were defined. An economic and technical evaluation of the applied CBM plan was carried out showing several benefits. The interesting outcome showed the validity of the process proposed in the case study for properly applying CBM, as well as its potentiality to be applied to other MHSs.

Keywords: material handling system; overhead conveyor; automotive industry; condition-based maintenance; sustainable manufacturing.

1.Introduction

Nowadays, high reliability, low environmental impact and safety of operations are important issues for every industry (Peng et al. 2010). Automotive industries have a huge impact on the society, the use of physical resources, the energy consumption, as well as the emissions to the environment: for these reasons, guaranteeing sustainable manufacturing for pursuing sustainable development, becomes essential. Due to the increasing global growth of vehicles requested by the customers, automotive industries, directly and indirectly, affect the economic wealth creation and impacts on the natural and human environment (Mayyas et al., 2012). Therefore, nowadays, ensuring sustainable production and high quality and environmental performance is a mandatory step to be competitive in the automotive sector (Savino and Mazza, 2016; Savino and Shafiq, 2018).

All business processes are responsible for sustainable production and must contribute to the achievement and the improvement of overall sustainable performance of organizations. Maintenance represents a key function for increasing availability and system efficiency, reducing lost production, avoiding unexpected plant downtime, guaranteeing low energy consumption, high safety human condition, and the decreasing of overall costs (Chang et al., 2013). Therefore, an efficient maintenance process has a large potential in the pursuit of sustainable manufacturing in automotive industries (Sari et al., 2015; Franciosi et al., 2017; 2018). Maintenance is essential for a safe system and more emphasis was put in the last years, compared to the past, on the relevance of reliable and sustainable performance of maintenance processes (Franciosi et al., 2019; 2020; Iung and Levrat, 2014; Laloix et al., 2016). For all these reasons, choosing the right maintenance strategy becomes essential. A critical activity of automotive industrial plants is the material handling system (MHS), which, being highly automated, requires effective and reliable maintenance processes. Periodic maintenance is often adopted on MHSs. Maintenance interventions and inspections are performed based on the indications of the manufacturers of such systems. This because, due to the high complexity of MHSs and their relevance for guaranteeing effective manufacturing processes, performing maintenance actions at systematic scheduled conditions is easier despite establishing a condition to monitor, based on which, maintenance tasks must be performed. Nevertheless, the adoption of a Condition Based Maintenance (CBM) for MHS consisting of monitoring the condition of mission-critical and safety-critical parts of a system, can avoid hazards rather than following a fixed schedule (Prapajati et al., 2012), considering the current real state of system degradation (De Carlo and Arleo, 2013). Consequently, an approach for defining the appropriate thresholds of diagnostic parameters to monitor in order to implement an effective CBM on MHSs could be relevant.

This paper addresses the issue of a proper implementation of CBM strategy on a real case study of an MHS (specifically, an overhead conveyor system) of an automotive company. Therefore, first, a general procedure for determining the parameter to monitor and its threshold value was provided. Then, the real case study concerning the overhead belt conveyor of a European automotive industry is presented to show the implementation of the approach. Case studies are especially useful to provide greater familiarity with complex problems, whose results are not clearly evident without analysis, experimentations and observations of the phenomenon on the field.

The paper is structured as follow: section 2 provides a theoretical background in the field of CBM, section 3 includes the proposed approach, section 4 presents the case study and finally section 5 the conclusions and further steps of the work.

2. Theoretical background

An effective condition based maintenance allows to schedule a maintenance task respect to the real time functioning condition of a system. This maintenance policy has been more adopted in the last years also thanks to the spread of the digital technologies that can favour the realisation of CBM programme (Fumagalli et al., 2019; Roda et al., 2018). The CBM approach leads to several advantages from economic, health and safety viewpoints. The CBM makes production systems more reliable, increases safety by detecting problems in advance before serious problems occur, which leads to the improvement of customer satisfactions due to the high-quality assurance (Shin and Jun, 2015). In addition, the CBM can optimize the production process and improve its productivity leading to several savings.

A literature analysis was carried out in order to investigate condition based maintenance models for material handling systems. Therefore, a research on Scopus database including the following strings of keywords "*material handling systems" or "conveyor systems" and "condition based maintenance"* was performed. Very few papers coherent with the objective of this work were found. Musselman and Djurdjanovic (2012) presented an intelligent condition based maintenance scheme for vibrations belt monitoring in a belt driven automated material handling system. Another interesting work was conducted by Stefaniak et al. (2016), who provided a procedure for determining decision thresholds based on statistical modelling of diagnostic data related to rotational speed of gearboxes utilized in a conveyor system. One year later Prakash et al. (2017) presented an integrated hidden Markov model approach to undertake fault diagnosis and maintenance planning for low-speed roller element bearings in a conveyor system. However, these three works are focused on the monitoring of a critic parameter of specific components of a material handling system and the adopted CBM approaches cannot be generalized for all MHSs. Thus, it could be relevant to have a general approach for defining the appropriate threshold of diagnostic parameters to monitor in order to implement an effective CBM on MHSs. Therefore, the existing CBM frameworks in the automotive industry were analysed. Prajapati et al. (2012) provided a breaf overview of condition based maintenance and presented a detailed discussion of CBM including applications of various methodologies and technologies that are being implemented in the field. Bousdekis et al. (2015) performed an extensive literature review in the area of decision making for CBM and identified possibilities for proactive online recommendations by considering real-time sensor data while Bousdekis et al. (2018) provided a deep literature review for prognostic-based decision support methods for CBM allowed them to identify the main CBM implementation steps. Finally, Voisin et al (2018) proposed an innovative approach based on machine degradation monitoring to anticipate part quality deviation from the consideration of joint product-process machine requirements. Moreover, they highlighted the steps required for machine monitoring. Based on these, the authors proposed a framework for proactive decision making in the context of CBM.

The aforementioned CBM frameworks include the main steps of CBM implementation which were analysed in order to support the implementation process of a proper maintenance management of material handling systems.

3. Methodology

A methodology to satisfy the automotive company's needs to reduce the unavailability of a critic overhead conveyor system was proposed. Therefore, after the analysis on the literature of CBM approaches, the main steps for the implementation of CBM plan were identified and presented in Figure 1.

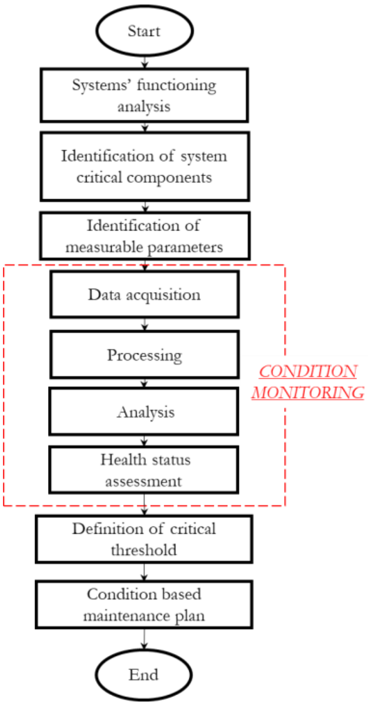

Figure 1 Procedure for the implementation of CBM plan

First, a technical "map" of the system through the analysis and the study of the operating system is carried out. The identification of the system's critical components through FMECA analysis constitutes the following step of the approach. The qualitative information extracted by failure mode and effects of each system critical component, can be integrated with quantitative information of system failures (Kothamasu et al., 2006). This makes possible the definition of the measurable parameters of the failure. To identify and establish a critical threshold, a data acquisition system must be implementedStatistical techniques are mostly used to define the thresholds for detecting the presence of faults (Peng et al., 2010). Various techniques and algorithms can be adopted, and generally they are validated on a large set of data. However, the available company datasets including failure information are often not robust and, therefore, the threshold definition is carried out through the examination of several breakdown events. Moreover, due to the high dependence on the industrial case for the definition of the critical threshold, several experiments to analyse data and to assess the health status of the system must be done. Finally, a program for the implementation of CBM plan based on a statistical analysis of collected data was detailed.

4. Case study

The case study presented in this article involves an overhead belt conveyor, a very common material handling system adopted in the assembly lines of the automotive industry. The procedure described in the previous section for the implementation of CBM plan was then applied on this case study.

4.1 System description

The case study considers three assembly lines (right side, left side and underbody) of a Bodyshop department involved in the production process for a car body of the automotive industry. The lines are composed of 14 workstations, connected by a conveyor, called Versapallet. The workpieces are moved from one station to the next by an overhead conveyor system, called Versaroll. Belt driven motorized rollers carry out the horizontal transfer of carriers, on which various body workpieces are loaded. The system ensures the automotive body workpieces are moved to and between workstations, where the operations, such as welding, are performed by robots, or other processing equipment.

In the workstations, a complementary system, called Versalift, allows the downhill of the carrier on the workstation equipment in order to obtain the assembly of the workpieces. The Versalift is a system that carries out the lifting and downing of the carriers, on the reference and locking equipment. When the carrier reached the final target position (where it must stop), the Versalift system lowers, allowing to perform the automatic welding operations, executed by robots, on the workpieces. Two elevators, integrated with Versaroll system, are placed at the beginning and the end of each production line, to move back each carrier; at the end of the production line there is a workstation reserved for maintenance work such as carrier extraction operations. The analysis carried out in this paper relates to the longitudinal length of the path of travel of the carriers to move between Workstations located along the path of travel. The components involved are 12 (Table 1).

The system uses an electric drive to generate and control the carrier movement along the path. The electric drive consists of a static power converter and a linear optical encoder, called Versacoder, which is composed by a fixed detection device and a grid device containing translucent areas and opaque areas, to control the positioning of the carrier. The closed loop carrier positioning system is gained thanks to an optical encoder.

The Carrier is supported on the plurality of rollers for the movement along the path of travel in response to rotation of the rollers by the motor.

Table 1 Versaroll system's components

N°	Components
1	Carrier
2	Driving pulley
3	Driven pulley
4	Synchronous belt drives
5	Gear motor
6	Encoder
7	Oval flange units
8	Toothed pulley
9	Detection device
10	Grid device containing translucent areas and opaque areas.
11	Electric drive
12	Programmable Logic Controller (PLC)

The Versaroll system is composed of a fixed part called, backbone, which contains the kinematic motion for the moving of the carrier (mobile part). The backbone consists of the gear motor, a driving roller and six driven rollers. Along with aligned linear segments of the carrier travel path, the power rolls are aligned with one another and interconnected with synchronous toothed belts for driving the interconnected rollers with a single moto in a way to transfer the rotational motion of the motor to the carrier. Figure 2 describes the operating scheme of the system.

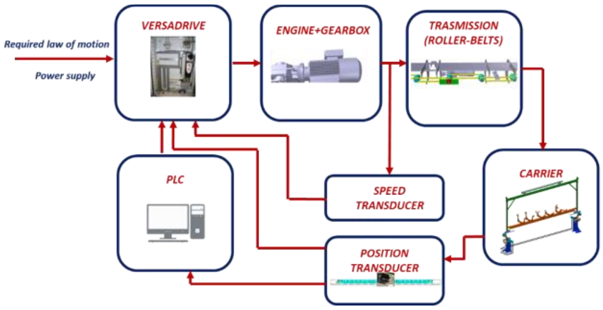

Figure 2 System operating scheme

The motor located at a WorkStation is a variable frequency reversible drive capable of transporting the carrier to the desired speed with a closed-loop control on the motor speed designed to obtain high precision in final positioning. However, overloading specific points at the beginning and stopping of the carrier path travel inside the workstation, after many cycles, leads to a phenomenon of localized wear, which results in the overshooting of the final target position of the carrier, leading to an unplanned downtime. For this reason, a significant loss of productivity is achieved. However, an efficient maintenance process can be considered as a solution to this problem.

Currently, time-based preventive maintenance is adopted on the system and replacements of components are performed based on regular intervals following the system designer’s recommendations. Nevertheless, unplanned downtime frequently occurred due to the failure of carrier final target positioning. This condition caused a production line stoppage with a consequent increasing in maintenance costs and availability reduction of the system. Therefore, the need for more suitable maintenance strategies was highlighted; in particular, the Condition Based Maintenance policy was identified as a possible solution to the described problem.

4.2 Identification of the system’s critical components

A FMECA analysis was conducted for discovering the critical components of the system. The occurrence (O), severity (S) and detection (D) scales were defined. The possible ways, effects and causes of failure were explained, both based on the data collected on maintenance interventions and on the study of the operation of the individual components. Risk Priority Number (RPN) of each of the systems’ components were calculated (Table 2).

Table 2 Equipment criticality

	Very Critical	**Critical**	**Less critical**	**Low priority**
Degree	AA	A	B	C
RPN	100-125	40-100	20-40	1-20
Item	Carrier	Versacoder, Synchronous belt drives, Oval flange units	Driving pulley, Driven pulley, Toothed pulley, Electric drive	Gear motor, Encoder, Programmable logic controller

The critical components (Carrier, Synchronous belt drives, Versacoder and Oval flange units) showed a low probability of failure detection since current design control cannot detect a potential cause/mechanism and subsequent failure modes. Furthermore, these components are critical because they do not have a well-defined wear-out life (failure probability is not a function of the working time but of the operating mode) and, indeed, the lifetime of the components are not the best approach to properly decide the processes of maintenance.

4.3 Identification of measurable parameters of the critical components

For each of the critical components, the monitoring parameters able to predict a potential failure on going were searched for. The results showed that is not possible, for how the system was designed and built, to know the state of wear. Consequently, the overshooting, defined as the difference between the position of the carrier along the path of travel and the final target position, is a suitable monitoring signal to provide information about the operating state of the system. Therefore, when the defined parameter overcomes a threshold value, it is possible to trigger an alarm and to plan maintenance work thus preventing the imminent failure.

4.4 Implementation of Condition Based Maintenance

In order to properly implement the CBM plan, some questions were fixed:

1) How to measure the overshoot respect to the target position?

2) Is it possible to link the overshooting phenomenon to an imminent downtime and distinguish if the breakdown is related to the fixed equipment (i.e. backbone) or the mobile equipment (i.e. carrier)?

3) How long can the gap be considered negligible taking into account the boundary conditions (for example load inertia, mechanical vibrations, noise, dust, temperature variations ...) that influence the system?

4) What is the maximum gap allowed, beyond which the alarm is triggered, and the action must be undertaken?

To answer these questions, a continuous monitoring of the overshooting position was carried out.

First, a data acquisition system on the on-board computer was implemented. The left side-line of the production system, which showed several signs of degradation, was chosen for the experimentation. Therefore, a program was implemented on the PLC in order to measure the phenomenon of overshoot. Such program, every 100 milliseconds, stores the positioning read by the Versacoder, during the carrier’s run in the station until final positioning, in order to estimate, if and how much the target final position, in which the carrier is expected to stop, is exceeded. The unit of measure of the output signal recorded by PLC is the step. One step corresponds to 0.8 mm of the linear travel carriers’ path.

When the carrier runs in the station, the sampling starts, and the positions are stored in the database of the on-board computer. Four machine states can be identified: absence of carriers, carriers in transit into the station, carriers in the final position, carriers in over-travel.

Using the described logic, the data relating to all the 14 carriers were extracted, and the machine states were measured.

Figure 3 shows the trend of the carriers’ run in the neighbourhood of the final target position, of a left side workstation. Until the carrier doesn't overshoot the final target position, it runs along its travel path in a perfectly healthy state. In this first experimentation, only 4 Carriers (N° 2,4,8,14) overshoot the final target position. Nevertheless, such carriers are still able to quickly return to the final stop position.

During the following days a progressive deterioration of the overshooting was observed. Figure 4 shows the overshoot values after 15 days on all 14 carriers running in the same station. A state of advanced overshooting with respect to the previous experiment is clearly evidenced.

In this case, the marked overshooting occurs when all carriers run in the station. In the same day of the experiment, a plant shutdown was reached due to not stopping of the carrier in the final target position of the station. An emergency maintenance work on the station was required. A wear related to the mechanical part of the station (Backbone) was found.

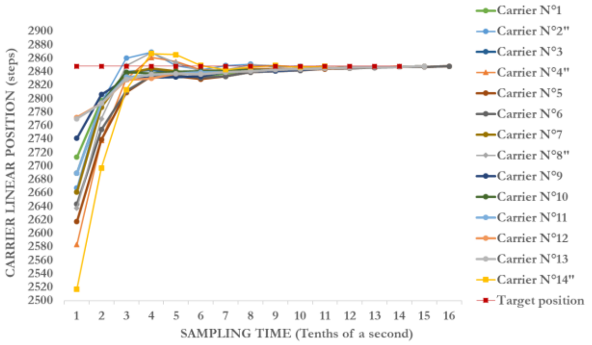

Figure 3 Overshoot of final position. 1st run

The overshooting parameter was monitored for about eight months, on all workstations of the left side-line. The maximum value of overshooting in each shift and for each station was recorded. Collected data showed:

- the overshooting parameter increases over the time;
- for all the workstations the failure has never occurred at regular time period;
- after the maintenance intervention overshooting parameter significantly decreases within a maximum range of 0-20 steps;
- in all cases the recorded last maximum overshooting value before a plant shutdown was within a range of 80-180 steps; moreover the 60% of the cases was within the range 80-120 steps.

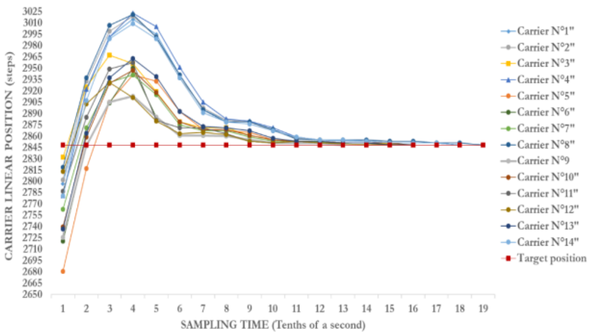

Figure 4 Overshoot of final position. Run after 15 days

Furthermore a "permitted overshooting" was defined. The monitoring showed that up to an overshooting value of 20, the parameter didn't affect the operating system due to boundary conditions influencing the working condition of the system. Within this threshold, the system can continue to work without the possibility of a failure occurs. Beyond this threshold, the system is in "unsafe overshooting" condition. The occurrence of this condition is due to some system components' wear. Therefore, inside the range of unsafe Overshooting, an alarm threshold for a maintenance work must be defined. In Figure 5, the maximum value of the overshooting parameter recorded before each failure was represented.

For this reason, the overshooting monitoring allows to plan effectively a maintenance work. Consequently, the definition of the overshooting threshold was performed. The threshold of overshooting parameter must be chosen in order to minimize the probability of unexpected plant shutdown and at the same time to perform a maintenance work only when really needed. Such threshold must ensure that, at any time of the day it is exceeded, the system must be able to work until the end of the working day (end of the second shift), allowing maintenance work in the third shift dedicated to maintenance activities.

In order to choose the threshold value, data relating to the evolution over time of the overshooting parameter until failure for all the 13 failure events observed was collected. An economic analysis which considered the expected cost of the failure and the cost of the preventive replacement, by varying the threshold value, was performed. Based on this analysis, the optimum threshold value was set to 80 steps. Corresponding to such value, the times between the threshold overshooting and the failure occurrence have a mean of 23 hours and a sigma value of 4.3 hours. Assuming that the failure probability during the wear phase of a system can be described through a normal distribution (Barlow et al.,1964), the system's failure probability before the end of the working day corresponds to an average of 2% and has a maximum value which is less than 5%. This is relative to the worst case, which happens if the critical alarm event occurs at the start of the first work shift and 16 hours of working remain before the preventive intervention.

Therefore, the threshold value of 80 ensures the completion of the two working shifts with the optimal probability of a plant shutdown.

The following step is to determine the logical structure of the CBM plan.

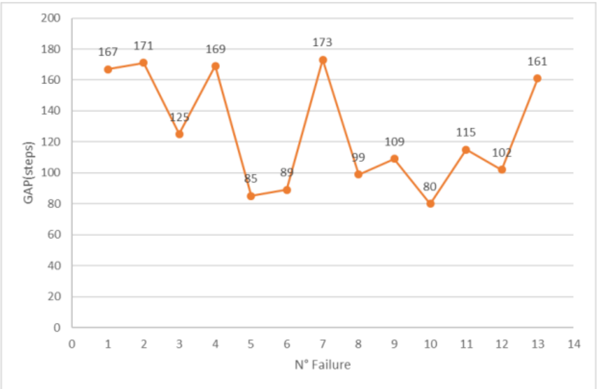

Figure 5 Trends of Overshooting parameter before failures

4.4.1 Implementation of maintenance plan

This section describes the proposed logical flow for the implementation of the condition based maintenance plan. Figure 6 shows the steps and the operations necessary for the maintenance program execution and reports the adopted notation.

The real-time monitoring of the overshooting parameter is necessary in order to implement the CBM plan. The monitoring cycle begins when the first carrier (N=1) is recognized by the Versacoder (condition $P_i \neq$ empty). The positioning of the carrier (P_i) along its path of travel is recorded until the target final positioning (P_{target}). In order to monitor the system working condition, the $Gap_{i,N}$ is estimated as the threshold, the CBM program must check if after 20 tenths of a second (Clock), the carrier is able to recover the overshooting in order to ensure the stopping in the final target position (condition $Gap_{i,N} = 0$). Otherwise, an emergency state due to an unexpected downtime of the system is activated. In such case, the wear is related to the station and then a maintenance work order for the station's Backbone is created, to be carried out at the end of the working day.

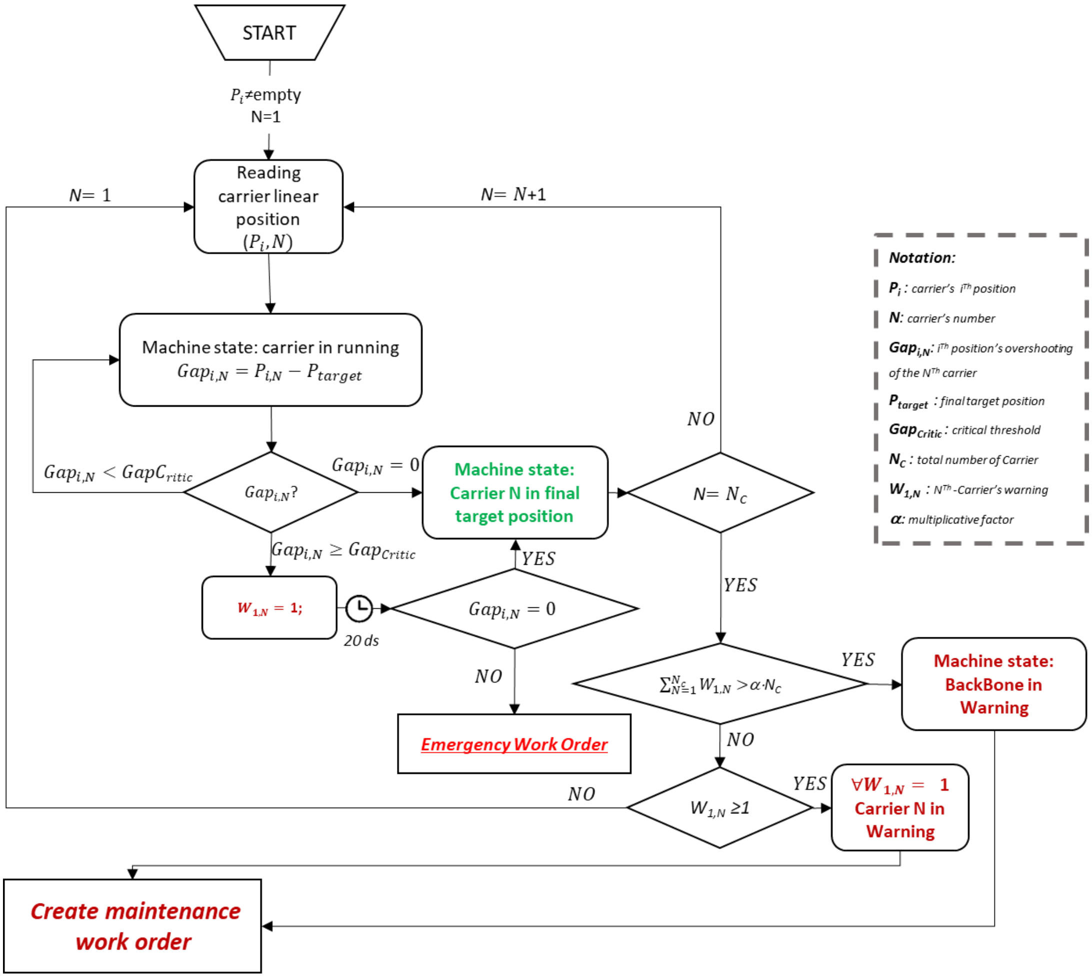

Figure 6: CBM logical diagram flow

Otherwise, a maintenance work order for each carrier that exceeded the critical threshold is created. In this first analysis the value of α is initially set to 0,7 because when the number of carriers with unsafe overshoot is more than 10 (on 14) the problem was found on the backbone. In this way, the procedure suggests the system's part (carrier or backbone) in which a possible breakdown is predicted. This real-time monitoring plan for the CBM implementation is performed for all stations of the production lines with Versaroll system transporting workpieces.

5.Conclusions and further research

Empirical evidence showed the difficulties for the practical implementation of CBM approach in an automated overhead transporting system, such as the identification of a critical measurable parameter to monitor the health status of the system as well as the definition of the critical threshold. The case study showed the necessity to follow systematic steps for developing a successful CBM plan. The new proposed maintenance strategy will allow savings in terms of plant unavailability, with a consequent increase in production capacity; maintenance intervention will be carried out only when it is required by the system; the savings about the replacement of materials will be obtained thanks to a better exploitation of the useful life of the components, which will be replaced only when the end of useful life is reached. Based on the interesting results showed by the study, the company would implement the new CBM strategy on all the overhead conveyor systems of the production assembly lines. The real challenge is upholding the highest standards of the production process. In order to reach this objective, future development involves a condition based-maintenance system completely integrated with production system also thanks to the potential of the emerging technologies of Industry 4.0. Moreover, the advantages coming from the effective CBM implementation in this case study, reveal the possibility to generalize the CBM logical flow for similar overhead conveyor systems in automotive industries and assist maintenance practitioners to develop a CBM plan for their specific context.

The future research will focus on improving the logical flow described, the definition of the critical threshold and the number of carriers, that implies a maintenance work for backbone. Prognostic methods based on real-time and historical data, like machine learning algorithms, will be applied in order to provide accurate recommendations for maintenance actions. However, these methods will be implemented only when the database, at the moment rather limited, will have a consistent size.

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