Towards Real Time Bottleneck Detection using Miniterms

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Abstract: The Sub-Bottleneck concept is introduced in this article for the first time. The literature defines the bottleneck concept through the cycle time in which, as a general rule, the slowest machine with longer cycle time, is classified as a bottleneck. Depending on the cycle time, the machine, the production line, the plant taken into account, etc., the literature has defined the concept of bottleneck in plant, bottleneck in production line, bottleneck in machine, etc. This article presents the Sub-Bottleneck concept for the first time. This concept uses the mini-term, a cycle time of each component that makes up a machine to determine which is the slowest and focus on future improvements that will optimize the efficiency of the production line. In order to validate this proposal, the mini-terms have been implemented in a production line at the Ford factory in Almussafes (Valencia, Spain), made up of 4 welding robots. The tests show the variable nature of the components and that the typical bottleneck studied in the literature does not have to coincide with the Sub-Bottleneck concept.

1 INTRODUCTION

The industrial network of a country plays a very important role in the country's own economy, this network is nothing more than the set of processes that are capable of transforming raw materials into a product. These processes have their maximum exponent in manufacturing lines where different machines apply a series of operations to a product that is transforming until it reaches its final condition (Garcia, 2016).

It would be difficult to understand the successes of any manufacturing company without taking into account the manufacturing lines and their evolution from the time of Henry Ford with the introduction of chain production to the present day with the revolution that new technologies are bringing about. This development seeks to improve one of the most important parameters of a production line: efficiency. High efficiency is a competitive advantage over other companies in the sector, the final objective is not only to make the product, but to do it with the greatest benefit possible and this benefit can be understood under one premise: maximize the time that the machine is productive.

Seeking to improve the efficiency of production lines, the industrial revolution in the 19th century was the point at which a new form of production emerged in which workers began to have specialized functions and use machines that increasingly helped to be more efficient both in quality and in the production itself.

The manufacturing industry is one of the industries where technology has had a great impact, going from having machinery that helped workers perform operations to having machines that are capable today of performing jobs that were previously carried out by several workers, again improving efficiency.

As we have seen, efficiency has always been and will always be one of the key points within this type of companies, which is why a measure called Overall Equipment Effectiveness (OEE) has been implemented, the OEE is a parameter used in the vast majority of the industries as it takes into account various fundamental indicators in the manufacturing

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process, such as availability, performance and even quality. Getting 100% OEE would mean that the machine has been working the entire time at full speed and without problems.

The concept of OEE was introduced in the OEE as part of the Total Productive Maintenance (TPM) methodology whose main objective pursues the efficiency of the machines of an industry (Hedman, Subramaniyan, & Almström, 2016).

Obtaining a 100% of OEE should be the objective to be pursued, however, this objective is difficult to achieve, especially when we talk about industries whose machines have been working non-stop for years and whose probability of failure increases considering the life span of the same. Here is another key concept, the maintenance of these machines whose fundamental objective is keeping them in optimal conditions.

For years when talking about maintenance within the operations of a factory, what is known as corrective maintenance and preventive maintenance were treated from two points of view (Li & Ni, 2009). The first happens as a result of a problem during the operation of the machine, which may be a stoppage or deterioration in the conditions of the machine that make it impossible to achieve the manufacturing objectives. The second concept aims to anticipate these stops through a temporary planning in which different checks are carried out on the machine, thus being able to have it in optimal conditions, generally for this reason. One of the keys to success to ensure that the machine is in optimal condition is the prioritization of maintenance orders (WO), the industry has had limited resources especially in recent times (Subramaniyan et al., 2020), in order to be able to prioritize the WO and therefore for many years the criterion has been based on the experts' opinion and the analysis of repetitive failures of the machines themselves along the time axis. These WOs will be carried out on a scheduled basis throughout the machine's useful life in opportunity windows (Chang, Ni, Bandyopadhyay, Biller, & Xiao, 2007) in maintenance, largely avoiding stops during production.

In the time planning of the WO we can ask ourselves: why carry out tasks on a scheduled basis?

New technologies offer us the possibility of obtaining information from machines in real time, which allows us to take a further step in maintenance by introducing the concept of predictive maintenance. Predictive maintenance proposes to carry out maintenance only when the machine really needs it and not on a scheduled basis like preventive maintenance does.

2 PARADIGM OF THE MAINTENANCE CURSE

In order to carry out an effective predictive maintenance system, this system should be able to monitor all the components in real time since, no matter how insignificant a component may be, it can fail and therefore cause a line stoppage. With current systems this approach would be viable only through the massive installation of sensors, vibration, temperature, etc. However, in an industrial environment this approach is completely unfeasible due to the high cost it would entail. This is what has been named as the paradigm of the maintenance curse. The necessary technology and algorithms are available but its massive use is unfeasible.

2.1 Short Terms

The works aimed at improving the efficiency carried out to date focus on implementing programmed WOs on an experience of failures of the machines themselves, however one of the main characteristics of production systems is their variability (Chang, Ni, Bandyopadhyay, Biller, & Xiao, 2006), no process remains constant over time due to the deterioration of the machines that make up this process. The data feedback given by the machines in real time manages to provide tremendously useful information so as not to depend on programmed WOs and to carry out maintenance when the machine really needs it, thus improving our efficiency not only at machine level but also at the level of resources of the company itself.

2.2 Real-time Monitoring

One of the keys to predictive maintenance lies in the ability to obtain information from the machines themselves. For a long time, most factories have worked with systems called Manufacturing Execution System (MES) that allow gathering information about production. However, nowadays thanks to the advances of new technologies we are able to collect a large amount of data about machines that could provide us with information not on production but on the health of the machine itself. Being able to know why a failure occurred thanks to the data collection allows us to pay special attention to the elements that caused the failure (Arne, Ylipää Torbjörn, & Bolmsjö Gunnar S., 2005).

If the way in which we consider this amount of data is changed in order to try to analyse this data immediately after it has been generated, this will allow us a new starting point within the maintenance paradigm, and for this we must consider two main steps (Chang et al., 2006):

- Real-time data collection and analysis.
- Dynamic corrections and WO planning according to analysed data.

2.3 Mini-terms

So far all previous studies have classified the data under two perspectives: long and short term.

Our line of work will be based on the use of a new paradigm introduced with the redefinition of the short term in smaller sub-periods, the Mini-terms, (Garcia, 2016; Garcia & Montés, 2018; Garcia & Montés, 2019).

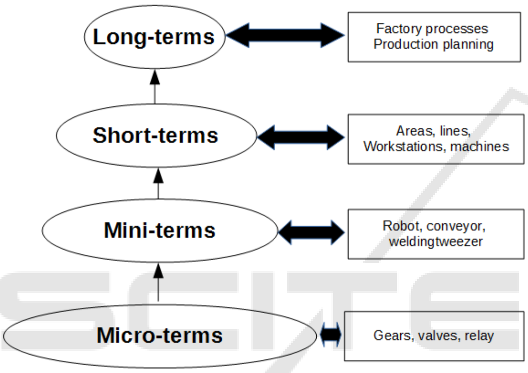

Figure 1: Pyramid of terms.

While the short term is defined as the cycle time it takes for a line, including a station, to perform its task, the Mini-term is defined as the cycle time it takes for the components of the line to do their task, as for example, pneumatic grippers, robot arms, clamps, cylinders, see figure 1.

Currently, the predictive maintenance approach from the Mini-terms paradigm has its maximum representation at Ford factory in Valencia where more than 16,000 pieces of equipment are controlled in real time. This control involves not only a 24-hour-a-day surveillance of each of the equipment, but an immediate response to the detection of deterioration of some element of the monitored equipment thanks to warnings generated in real time that reach the maintenance teams, these warnings generate two outputs simultaneously, one by email, and the other by sending a message to any mobile device. In both cases, an image at the time of deterioration and the information corresponding to the line and station are attached within these warnings, optimizing the response time by the maintenance team (Garcia & Montés, 2019).

3 BOTTLENECKS

As indicated in the introduction, production lines and their components/ machines do not have an ideal behaviour, and in addition, during their useful life their behaviour may change. This implies that a certain degree of imbalance is inevitable and therefore, generating a time loss and turning the element that suffers this time loss into what is known as a bottleneck.

Most of the studies carried out to date try to identify bottlenecks by associating them with unplanned production shutdowns (Subramaniyan et al., 2020), that is, shutdowns largely due to machine failures. Trying to minimize these types of stops will make the machine's OEE increase and therefore the bottleneck will no longer happen.

Throughout the literature dedicated to the study of bottleneck detection, different approaches have been made (Betterton & Silver, 2012), showing two types of states within the operation of a machine, active and inactive state, (Subramaniyan et al., 2020) the first being any state in which the machine is operating without waiting, while in the second the machine is stopped due to a wait either because it cannot continue because the next operation is blocking it or because it cannot start a new operation as it does not have the necessary elements to start it: called starved, see figure 2.

Currently, bottlenecks are always associated with short and long-terms, therefore, the bottleneck from the perspective of a line will be a station while from the point of view of management it can be an entire line or even a plant.

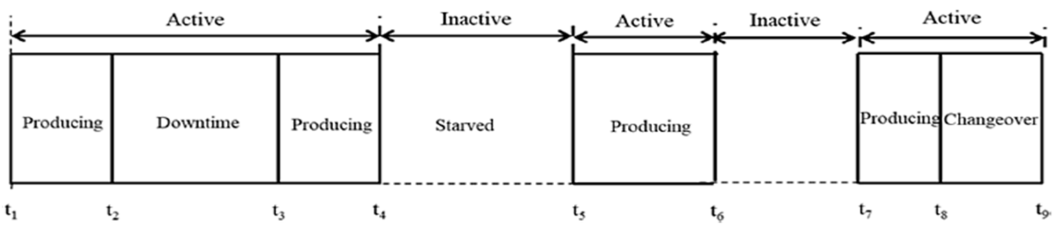

Figure 2: Operating states of a machine.

In this article we propose to use the Mini-terms, the cycle time of the components, to detect what has been called Sub-Bottlenecks in order to determine which component of the machine is behaving as a bottleneck. Section 4 presents the definition of Sub-Bottlenecks, section 5 presents the actual study performed at a station where Sub-Bottlenecks have been measured. Section 6 concludes with a discussion of the preliminary and future results.

4 SUB-BOTTLENECKS

Based on the classification of cycle times defined in Figure 1, we can define bottlenecks as shown in Figure 3.

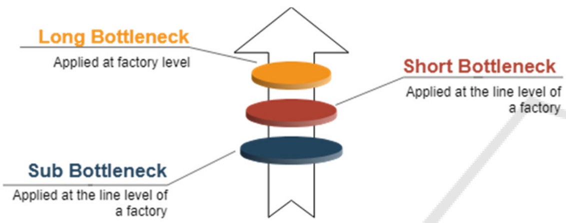

Figure 3: Pyramid of bottlenecks.

A Sub-Bottleneck can be defined as the equipment that has a Mini-term longer than the rest of the equipment in the line.

This article will focus on the analysis of the Sub-Bottlenecks.

5 VALIDATION

To validate the relevance that Sub-Bottlenecks may have in production, this study will focus on welding stations. Welding units are one of the most commonly used equipment in the automotive industry. This usually consists of a robot arm and a welding clamp, see figure 4. Welding lines usually consist of several pieces of equipment that can work both in series and in parallel. Although the welding units are made up of the same components, their state of deterioration may not be the same from one unit to another.

In this study, we have chosen a station of a welding line at Ford Valencia automotive factory, this manufacturing line called 7 includes one station which consists of four welding robots, two placed in the left part of part R1, R3 and two on the right side, R2 and R4.

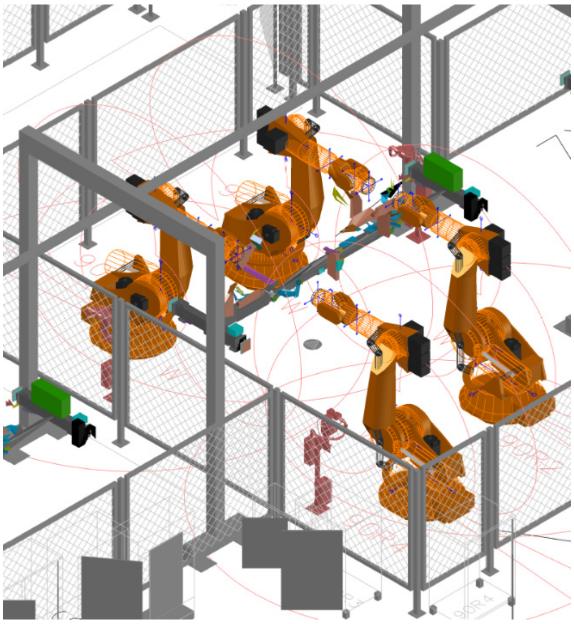

Figure 4: Weld line 7 – Ford Valencia.

In this station we have carried out the assembly of a sub-set of the left side of one of the models manufactured within the factory, this assembly begins when a part enters the station and at that moment the clamps close to ensure the position of the part, once all the clamps have been closed, the work signal is activated for the four robots. Each of the four robots must perform a series of welding points on the part to ensure its integrity.

We will redefine for each of these robots their cycle time from the perspective of Mini-terms, with which we will obtain that:

$$T_{CRi} = T_{HtW} + T_M + T_W + T_{SB}$$

Where:

- $TC_{,R1}$: Cycle Time is the total time the robot takes to do the necessary work on the station.
- THtW: Home to Wait Time is the time that the robot uses from the first position, called Home Position to the waiting position before starting to work, this position is a safe position to which the robot always goes back and it happens before the part is correctly positioned.
- $_{TM}$: Move On Time is the time in which the robot is in motion from the start of the job until it is finished.
- $_{TW}$: Welding Time is the time in which the robot is performing its work, in this case making welding points on the part.

- TSB: Starved/Blocked Time is the time in which the robot is stopped waiting to be able to carry out its work either due to lack of parts (Starved) or because it cannot continue since subsequent stations prevent the part from coming out (Blocked).

The diagram in Figure 5 shows the distribution of sub-cycles times that make up the cycle time of a welding station.

All Mini-terms are programmed in the line's PLC, and the values obtained are sent to a NoSQL database called Miniterm4.0 database. In table 1 we can see the exact value of sub-cycle times of the station in line 7 in a specific cycle.

Table 1: Division of sub-cycle times of station in line 7. The time marked in red indicates that this robot is the Sub-Bottleneck.

	CycleT ime	Home To Wait	Robot MoveOn	Welding Time	Waits
R1	43,76 s.	0,59 s.	12,15 s.	19,04 s.	11,98 s.
R2	43,88 s.	0,25 s.	14,76 s.	17,51 s.	11,36 s.
R3	43,94 s.	0,40 s.	13,79 s.	19,51 s.	10,25 s.
R4	43,64 s.	0,40 s.	10,92 s.	15,78 s.	16,54 s.

With the current bottleneck methods, we would only have the first column as data to analyse and therefore the efforts would be focused on R3, however, if we continue checking table 1 we can draw conclusions that we could not even come up with when using the current methods of bottlenecks.

By using each column as an independent variable of the system, instead of analysing the R3 as the only bottleneck to analyse we could analyse the different bottlenecks according to the Mini-terms, that is, to analyse the Sub-Bottlenecks so we could determine that:

- Home To Wait: The R1 is the bottleneck.
- Robot Move On: The R2 is the bottleneck.
- Welding Time: The R3 is the bottleneck.
- Waits: The R4 is the bottleneck.

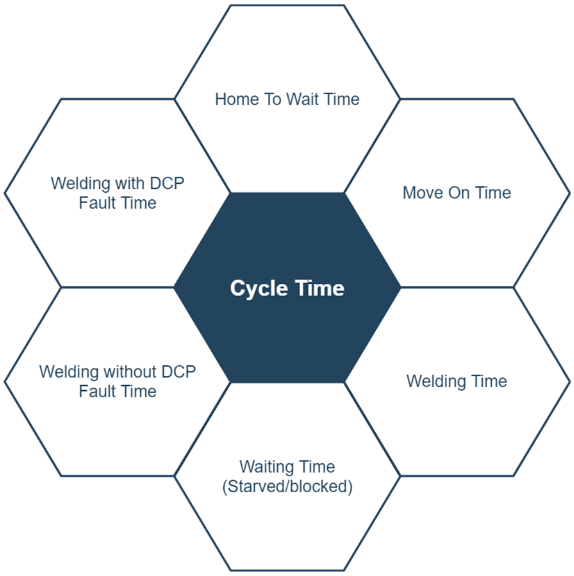

Figure 5: Sub-cycle time diagram.

Another characteristic we can observe throughout several executions of the system is that the Sub-Bottleneck is dynamic, so when depending on the set of operations that take place in the station, it can vary from cycle to cycle, however, despite the fact that this variability exists we will consider as Sub-Bottleneck the maximum time repeated. Next, we can see the execution of several cycles of the station in line 7 and the evolution of the Sub-Bottleneck throughout those cycles, see table 2.

6 CONCLUSIONS

In this article, the Sub-Bottleneck concept, the bottleneck component, has been defined for the first time. The detection of Sub-Bottlenecks is a fundamental step in predictive maintenance, it is not only capable of identifying, thanks to the fundamentals of Miniterms, which elements of a

Table 2: Evolution of SubBottleneck over several execution cycles. The red marking indicates that it is the SubBottleneck.

Minibottlenec R1 Time Analysis				Minibottlenec R2 Time Analysis				Minibottlenec R3 Time Analysis				Minibottlenec R4 Time Analysis			
Home To Wait	Robot MoveOn	Welding Time	Waits	Home To Wait	Robot MoveOn	Welding Time	Waits	Home To Wait	Robot MoveOn	Welding Time	Waits	Home To Wait	Robot MoveOn	Welding Time	Waits
0,66 s.	12,29 s.	19,32 s.	12,12 s.	0,25 s.	14,07 s.	17,33 s.	11,94 s.	0,41 s.	13,87 s.	19,21 s.	10,08 s.	0,50 s.	10,73 s.	15,73 s.	16,91 s.
0,62 s.	12,36 s.	18,95 s.	12,20 s.	0,37 s.	13,99 s.	17,43 s.	11,99 s.	0,40 s.	13,85 s.	19,88 s.	10,15 s.	0,53 s.	10,83 s.	15,60 s.	17,04 s.
0,62 s.	12,36 s.	18,95 s.	12,20 s.	0,37 s.	13,52 s.	17,43 s.	11,99 s.	0,40 s.	13,85 s.	19,88 s.	10,15 s.	0,53 s.	10,83 s.	15,60 s.	17,04 s.
0,52 s.	12,35 s.	18,92 s.	11,95 s.	0,21 s.	14,02 s.	17,41 s.	11,74 s.	0,37 s.	13,75 s.	19,45 s.	10,32 s.	0,43 s.	10,94 s.	15,64 s.	16,60 s.
0,52 s.	12,35 s.	18,92 s.	11,95 s.	0,21 s.	14,02 s.	17,41 s.	11,74 s.	0,37 s.	13,75 s.	19,45 s.	10,32 s.	0,43 s.	10,94 s.	15,64 s.	16,60 s.
0,68 s.	12,31 s.	18,88 s.	11,83 s.	0,34 s.	13,88 s.	17,36 s.	11,72 s.	0,47 s.	13,85 s.	19,42 s.	10,10 s.	0,53 s.	10,64 s.	15,71 s.	16,68 s.
0,68 s.	12,32 s.	18,77 s.	11,95 s.	0,31 s.	13,75 s.	17,39 s.	11,80 s.	0,47 s.	13,89 s.	19,37 s.	10,09 s.	0,49 s.	10,68 s.	15,57 s.	16,86 s.
0,56 s.	12,47 s.	19,10 s.	11,99 s.	0,15 s.	14,20 s.	17,45 s.	11,67 s.	0,31 s.	13,90 s.	19,05 s.	10,29 s.	0,34 s.	10,80 s.	15,69 s.	16,86 s.

manufacturing line are affecting the OEE in real time, but it is also capable of opening a unique range of line optimizations.

One of the conclusions that we can draw from the present study is that the bottleneck examined in the literature so far does not have to coincide with the same one identified by the Sub-Bottlenecks, in fact in a station we will only find the typical bottleneck and a Sub-Bottleneck per Mini-Term analysed.

Being able to subdivide the times of each element of the line as we have seen allows us to know, for example, which robots have a higher workload, welding time, despite not being the bottleneck, and this could allow us to rebalance operations. We could also identify which elements have longer waiting times, to which we could apply speed reduction algorithms in real time with the aim of providing a lower consumption.

Our future work will be focused on two lines. Firstly, the use of the information provided by the Sub-Bottlenecks in order to improve the efficiency of the production lines. Secondly, the improvement of the subdivision of the welding line in mini-terms in order to detect the Sub-Bottlenecks more efficiently. For example, the times that there could be during the welding process due to failure of this.

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