A Novel Model to Analyse the Effect of Deterioration on Machine Parts in the Line Throughput

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Abstract: This paper presents evidence on how the variability of machine parts can affect the throughput of an assembly line. For this purpose, a novel model based on mini-terms and micro-terms has been introduced as a machine subdivision. A mini-term is a cycle time subdivision that can be selected by the user for several reasons: the replacement of a machine part or simply to analyse the machine more adequately. A micro-term is a mini-term subdivision and it can be as small as the user wishes. Therefore, the cycle time of a machine is the sum of mini-terms or the sum of the micro-terms. This paper focuses its attention on a welding line in a Ford Factory located in Almussafes (Valencia) where a welding unit was isolated and tested for some particular pathologies. This unit is divided in three mini-terms: the robot motion, the welding motion and the welding task. The cycle time of each mini-term is measured by changing the deteriorated components for others in the time. The deterioration of a proportional valve, a cylinder, an electrical transformer, the robot speed and the loss of pressure are tested within a range that cannot be detected by alarms and maintenance workers, that is, the range of normal production. The real welding line is modelled and a novel simulation algorithm is created based on mini-terms. The experimental measurements are introduced in the simulation model and the effect of the pathologies in the production rate is computed. As a result, the pathologies with greater variability have a deeper impact in the production rate mainly due to the bowl phenomenon effect. On the contrary, the pathologies with low variability have a low effect in the production rate. In fact, this paper demonstrates that the maximum rate capacity can be achieved if the machine variability is near zero.

1 INTRODUCTION

A production line is a set of sequential operations established in a factory whereby materials are put through a refining process to produce an end product that will be suitable for onward consumption; or where components are assembled to make a finished item. Because of the high investment and running costs involved, the design of such lines is of considerable importance, (O.Battaia and A.Dolgui, 2013). There are a large number of crucial decisions to be made in flow line design such as, product design, process selection, line layout configuration, line balancing, machine selection, available technology, etc. Usually, these problems are considered one at a time because of their complexity, (O.Battaia and A.Dolgui, 2013).

The last and crucial step in the process design is line balancing, (O.Battaia and A.Dolgui, 2013). It's here where tasks will be assigned to the workstations and resources will be used in the line (this is a complex combinatorial problem and the solution mostly determines the efficiency of the line designed). Due to the relevance of this task, a large number of researchers have been working on this topic ((O.Battaia and A.Dolgui, 2013) represent a state-of-the-art understanding in the matter). Depending on industrial environments, there are solutions to a number of product models, line layout, tasks and their attributes, workstations and their attributes, etc, see (O.Battaia and A.Dolgui, 2013). Currently, one of the important topics under assembly line design and balancing is the task processing time variability engendered by the following factors, (E.Gurevsky et al., 2012): in-

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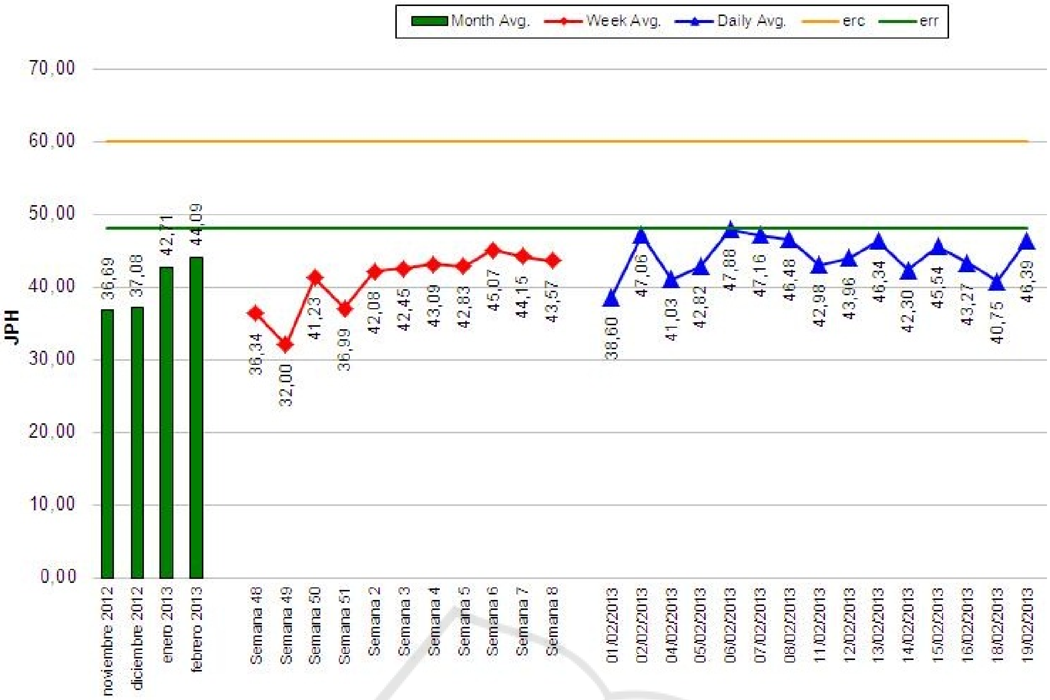

Figure 1: Jobs Per Hour produced in a real line production VS idealized production rate. Note: ECR (engineering running capacity). ERR (engineering running rate).

stability of operators performing tasks with respect to work rate, skill and motivation; materials of different composition of product items; changes in products and workstation characteristics; as well as failure sensitivity, (E.Gurevsky et al., 2012). In particular, more papers were published in the last years about learning and ageing effect, see (Janiak et al., 2011), where the mean value and standard deviation are often used for model task times.

At the beginning of modern production systems, as well as in most research papers about line balancing problems, (O.Battaia and A.Dolgui, 2013), it was thought that a 'perfectly balanced' line was the most efficient line design. However in practice, the perfect balanced line seldom exists, because some degree of imbalance is inevitable. When the line is designed by an expert team, a maximum production rate is defined, mainly in jobs per hour (JPH). It is known as "Engineering Running Capacity" (ERC). The factory employees will concentrate on the task of achieving this maximum production rate, see Fig.1, defining the throughput of the line. Reality shows that the ERC is extremely difficult to achieve so the factory defines a new maximum production rate that is more realistic and is known as the "Engineering Running Rate" (ERR).

Recent studies have shown that unbalanced lines with a bowl shape workload configuration can yield performance in throughput as good as, or even better than perfectly balanced lines. It is known as a "bowl phenomenon". This phenomenon has been studied in literature during the last decades. It determines that if we introduce a higher load to the beginning and end workstation, the throughput can be increased. More recently a study of the bowl phenomenon was presented in large unpaced assembly lines under stochastic processing times. The results of this study suggest that unbalancing a large assembly line in a bowl shape workload configuration could provide statistical significant improvements in throughput. In this study, single bowl configuration and multiple bowl configurations are tested, see (C.E.Lopez, 2014).

The present paper develops a novel simulation tool that will allow us to know in real-time the throughput of the production line. This novel tool uses two new data classifications, the mini-term and the micro-term, (E.Garcia, 2016), (E.Garcia et al., 2018), (E.Garcia and N.Montes, 2019). The literature classified the data used in the analysis into long-term and short-term. The difference between both terms has been addressed by (Chang, 2005). Long-term is the cycle time mainly used for process planning, while short-term is the cycle time focused primarily on process control. A mini-term is a short term subcycle time subdivision and a micro-term is a mini-term subcycle time subdivision.

The goal of the present study is to determine how the production rate and bottleneck location are affected by the mini-term variability and with some deterioration machine parts that are not detectable by the control system of the machine and also by maintenance workers. For instance, the stiffness of a proportional valve, the pneumatic cylinder wear, galling or communication inside the stem, the loss of the wire insulation in a transformer, the loss of pressure in a pneumatic circuit (below the alarm value) and the loss of the robot speed. All of these pathologies are measured in a real welding unit. In order to test the effect of the measured pathologies, a real welding line is modelled. In particular, a real welding line in Ford S.A. located in the factory in Almussafes. This line has 35 welding units distributed in 8 workstations. The simulation results provide jobs per hour (JPH) due to the analysed pathologies. The paper is organized as follows. Section 2 presents a mathematical model to compute the long-term and short-term by means of the mini-terms and micro-terms. Section 3 presents a real case study, which is a welding unit where mini-terms are measured experimentally for particular pathologies. Section 4 presents a model of a real welding line and the simulation results for each of the pathologies. Section 5 presents a discussion on the results and Section 6 concludes the paper with an emphasis on future research challenges.

2 FROM THE MICRO-TERM TO THE LONG-TERM

The literature classifies the data used in the anal- ysis into long-term and short-term cycle time. Long- term is mainly used for process planning while short- term focuses primarily on process control. There is abundant literature for long-term analysis in com- parison with the literature that studies short-term data.

Therefore, following the definition by (L.Li et al., 2009), the short-term is referred to an operational period not large enough for a machine's failure period to be described by a statistic distribution. The machine's cycle time is considered short-term. The present study redefines short-term cycle time into two new terms, mini-term and micro-term. A mini-term could be defined as the cycle time of a machine part that, in a preventive maintenance policy or in a breakdown, could be replaced in an easier and faster manner than another machine part subdivision. Also a mini-term could be defined as a subdivision that allows us to understand and study the machine behaviour, see figure 2.

Each mini-term is modelled statistically by the mean value μ and standard deviation σ of the mini-term cycle time, $Tm^j(\mu^j_{Tm},\sigma^j_{Tm})$. Then, the mean value of the short-term machine cycle time for a machine $i(\mu^i_{TC})$ can be computed as;

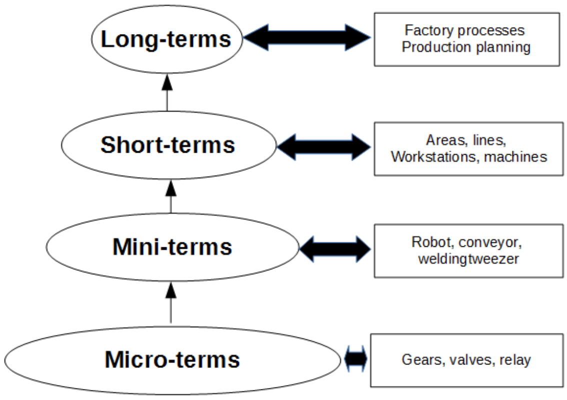

Figure 2: From Micro-term to Long-term.

$$\mu^i_{TC} = \sum_{j=1}^{n} \mu^j_{Tm} \quad (1)$$

where μ^j_{Tm} is the j mean value of each mini-term cycle time. The standard deviation of the short-term machine cycle time for a machine $i(\sigma^i_{TC})$ can be computed as;

$$\sigma^i_{TC} = \sqrt{\sum_{j=1}^{n} {\sigma^j_{Tm}}^2} \quad (2)$$

where σi_{TC} is the j standard deviation of the short-term machine cycle time. In the same way, a micro-term is defined as each mini-term part in which could be divided itself. Each micro-term is also modelled statistically by the mean value and standard deviation of the micro-term cycle time, $T^k_\mu(\mu^k_{T\mu},\sigma^k_{T\mu})$. Then, each mini-term is defined as:

$$\mu^j_{Tm} = \sum_{k=1}^{n} \mu^k_{T\mu},\ \sigma^j_{Tm} = \sqrt{\sum_{k=1}^{n} {\sigma^k_{T\mu}}^2} \quad (3)$$

Now, the next step to move upward in the pyramid of figure 2, is to simulate the workstation joined with the other ones. The common way is using a simplified machine state, see Figure 3 . There are three possible workstation states, "Working", "Starving" and "Blocking". If the current station is in "Working" state and the work is finished, it checks the following station, if it is in "Starving" state, the finished part of product is delivered to it and the state of the current station is free to receive another job. If the next station is in "Working" state when the current one finishes its work, the current station changes its state to "Blocking", that is, blocking itself until the next station is free. If the current station is free to receive another part, it checks the previous station. If the previous station is in "Working" state, the current state changes to "Starving" state waiting itself until the previous station has a part to work on. If the previous station is in "Blocking" state, the current station receives the part and the current state changes to "Working". There is always work available for the first station and there is always a final product to be taken from the last one. When the simulation starts, every station state is set to "Starving", but the first one whose state is set to "Working" state. The simulation loop runs at predefined step time ($\triangle t$). For each step time, the cycle time of each workstation decreases until the cycle time is zero, meaning that the work is finished and the events are triggered. The cycle time of a workstation has a probabilistic distribution $TC_i(\mu^i_{TC},\sigma^i_{TC})$ that depends on mini-terms and micro-terms, see equations (1) to (4). Then, when a new job is started in a workstation, a new cycle time is generated based on the probabilistic distribution. It also means that the Starving and Blocking states have a probabilistic time distribution that is, $TS_i(\mu^i_{TS},\sigma^i_{TS})$, $TB_i(\mu^i_{TB},\mu^i_{TB})$, respectively. At this point the latency time is also defined, which determines the rate with which a finished part is extracted from the workstation, $LA(\mu_{LA},\sigma_{LA})$. The jobs per hour produced by the line, $JPH(\mu_{JPH},\sigma_{JPH})$, are computed using long time simulation. If we increase the time simulation for the lifetime of the factory, the total production can be computed, see figure 2, the upper part of the pyramid.

3 CHARACTERIZATION OF MINI-TERM DETERIORATION IN A REAL WELDING STATION

The goal of the present study is to demonstrate the effect of deterioration of some micro-terms on the throughput of the line. For this purpose, a welding line is taken as an example. The welding lines are one of the most relevant because there are 4.500 welding points in a car. The welding line is composed by welding workstations which have welding stations working in parallel, see section 4. A welding station is composed of a robot arm and a welding clamp, see Figure 4. In the present study, a welding station was isolated for the welding line in order to analyse, understand and measure the results presented in this section.

The behaviour of the welding unit is simple. First, the robot arm moves the welding clamp to the point to weld. Then, a pneumatic cylinder moves the welding clamp in two phases: one to approximate the clamp and the second one to weld. The pressure applied by the clamp is controlled by a control system. Each of these devices needs a certain time to develop their task and within each of these devices, there are also components that need a certain time to develop their own tasks. In order to analyse the deterioration effect of some micro-terms, the welding unit is divided in three mini-terms, the robot arm, the welding clamp motion and the welding task.

Figure 5 shows the experimental setup to measure the cycle time of each mini-term in the welding station where the PLC and the PC are used to measure the time. The experimental test is quite simple. The robot arm, starting from a predefined initial point, moves the clamp to a predefined welding point; the clamp is closed and develops the welding task. Due to the welding motion and the welding task that are low time consuming, the task is repeated 6 times.

3.1 Pathologies Analysed

The welding station, as well as other stations in the industry, could suffer an amount of pathologies that produce an effect on the cycle time. Based on the operator's experience, we selected some pathologies for a welding clamp station. These pathologies produce a cycle time modification but fail to produce the rupture of the component, going unnoticed for maintenance workers and also for the control system that has some alarms to trigger fails. The pathologies for the welding clamp mini-term are: the proportional valve, the cylinder stiffness, welding failure produced by the transformer and the pressure loss, and the pathology for the robot arm mini-term is: the robot arm speed. A brief description of each one are hereby explained:

- Pathology 1 (Proportional valve): This valve transmits the pressure to the cylinder and the controller controls it. It is responsible for maintaining the proper pressure in the cylinder. During its lifetime, its components suffer deteriorations that produce the stiffness of some of them. This condition creates a time delay. When the deterioration is big enough, the valve cannot transmit enough pressure to the cylinder and the welding task cannot be carried out.

- Pathology 2 (Cylinder stiffness): A critical term in welding resistance is the pressure force on the metals together. This force is necessary to ensure good electrical contact between the parts to be welded, and to maintain the fixed parts until the metal forming the solid board has time to solidify. The elements responsible for transmitting the proper pressure to these plates are cylinder clamps. In this case, one of the

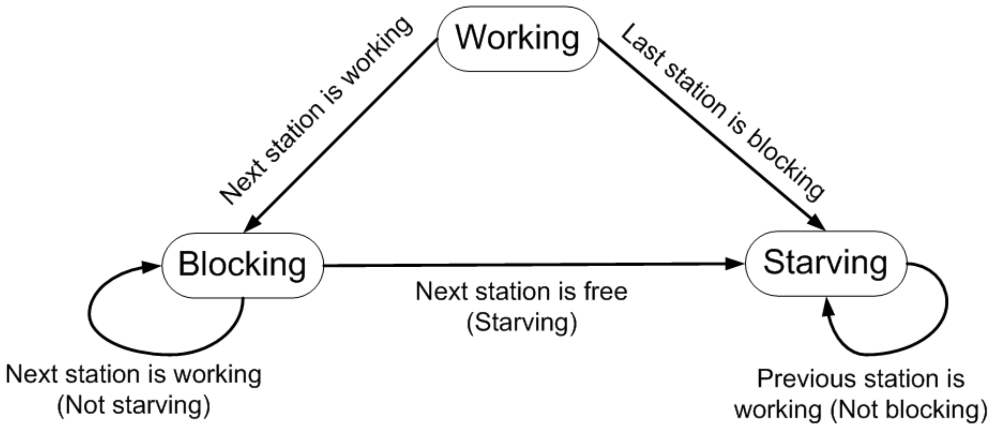

Figure 3: Simplified machine state for the workstation.

Figure 4: Welding station.

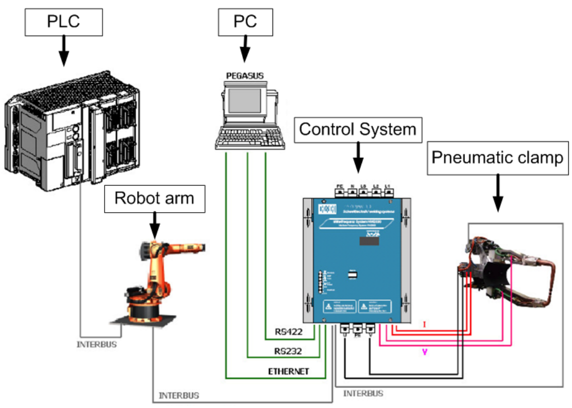

Figure 5: Experimental setup for the welding station.

cylinders could have a wear, galling or communication inside the stem. This condition creates a time delay. Maintenance workers detect this pathology when the cylinder cannot transmit enough pressure on the metals and the welding task cannot be performed.

- Pathology 3 (Welding failure): The welding process between parts consists of passing an electric current through intensive metals to be joined. The device generally used for this task is a transformer. The power goes through a transformer in which the tension is reduced and the current is increased substantially. The fatigue of this component is mainly produced due to the loss of wire insulation. A modification is carried out in the value of the insulated resistance and therefore a current reduction is produced affecting the welding time. Maintenance workers detect this pathology when the failure is so big that the welding task cannot be performed.

- Pathology 4 (Pressure loss): One of the most common delays is produced by pressure losses in a pneumatic circuit. The pressure drop causes a delay or malfunction in the pneumatic devices to be operated. This pathology could be produced by many facts such as a simple pore that produces a failure in the compressor. Maintenance workers detect this failure when the low pressure alarm is triggered.

- Pathology 5 (Robot speed): The common industrial robots have 6 axes. All these axes (motors) are synchronized to achieve the points that have been defined by the program to perform its function or task. If we have a failure in the operation, it causes an engine speed reduction that directly affects the process cycle time. There is an amount of reasons that produce this pathology. In these industrial robot arms, high speed and high accurate operation are required. However, in the case of high speed operation, it often causes high jerk, i.e., rapid change of acceleration. Jerk causes deterioration of control performance such as vibration of a tip of a robot arm. Jerk forces are not equally distributed and as the robot arm does the same movement again and again, the deterioration is located in some particular joints. Mechanical structure deterioration or the deterioration of electrical parts also affects the speed. This pathology is very difficult to detect by the maintenance workers because it does not produce the breakdown of the machine and, as the robot moves at high speed, it is nearly impossible to be detected without a specific procedure.

3.2 Experimental Test

The experimental methodology is as follows. The clamping task is to weld the same point 6 times in order to obtain enough time precision. The robot arm trajectory is the same in all the movements. Then, the clamping task is repeated 40 times in order to obtain a sufficient number of samples to measure the mean value and the standard deviation for each mini-term. First, the welding clamp station is tested without any of the pathologies hereinbefore explained. Afterwards, a particular component with each pathology is replaced in the station and the test is repeated. It is important to remark that the components are in the normal production rate. Table 1 shows the experimental result measurements of all pathologies for each mini-term. $(\bar{x}, S)$.

4 WELDING LINE. MODELLING AND SIMULATION

A previous section shows how the welding unit and, machines in general, have a probabilistic behaviour. In addition, the deterioration of the machines produces a delay in the intermediate task and/or in the standard deviation. In this section we will analyse how many jobs are lost in a real line due to these pathologies. For this purpose, a real welding line in Ford S.A. located at the Almussafes factory has been selected. The welding line was installed in 1980. The staff group that designed the line defined the maximum running capacity, ECR (engineering running capacity), 60 JPH. However, the plant engineers have another maximum running capacity, that is the ERR (engineering running rate), in this case defined in 51 JPH. And our daily production to reach is GRR (Get Ready Requirement) our (28,9 JPH). The GRR means market requirements, i.e. customers' orders. Figure 6 shows the production rate of the welding line.

In a real welding line like this, there are welding workstations where, each one of them has welding stations working in parallel and sometimes in serial. Each welding station makes some welding points in the same cycle time. We can find 1, 2, 4 or at least 6 welding stations in the same workstation, where each one of them makes up to 19 welding points, see table 3. In our particular case, our welding line has 8 workstations where 3 are for 6 welding units, 4 with 4 welding units, and 1 for 1 welding unit. Each welding unit is modelled with robot motion, welding motion, welding task as well as the offset. Robot motion means how many seconds the robot is moved, the welding motion and welding task mean how many welding points the welding clamp has to perform. The offset means how many seconds the welding station must wait for another station to do the job.

5 WELDING LINE SIMULATION

In order to simulate the welding line, a state machine simulator is developed. There are three possible workstation states: "Working", "Starving" and "Blocking", see figure 3 and figure 7. The loop is updated with an incremental time of 0.01 seconds. In the simulated welding line, there is always a job in the first workstation, so that the blocking state cannot happen in the first station. In addition, all the jobs finished in the last workstation are removed, so that the "Starving" state in the last workstation cannot happen. The loop starts with all the stations in the "Blocking" state.

The cycle time for each workstation is the maximum cycle time of each welding station that works in parallel, indicating the slowest welding unit and the bottleneck for a particular workstation. The transfer time is added to the cycle time. This time is the time required to transport the car from one workstation to the next one (12 seconds), see figure 8.

The cycle time of each welding unit is computed as shown in figure 9. A pseudo-random number based on mean and variance is computed for each mini-term using the experimental values of table 2. The algorithm repeats the creation of a number as many times as the mini-term is repeated (i.e. for 10 welding points, the algorithm will produce 10 numbers). The offset is also added if necessary. The simulation is computed with two time bases, one hour (JPH) and one day (JPD) with an incremental time of 0.01 seconds. This simulation is repeated 50 times and the mean and variance of the jobs produced are computed. First, the simulation with any pathology is performed. The results are for one-hour time base, (51,1.05) JPH, similar than the ERR, and for one-day time base, (1252, 3.09) JPD. Table 2 shows the simulation results where a particular pathology is located in a particular welding station. Obviously, the rest of welding units are considered without pathology.

Table 1: Mean and standard deviation values for the robot motion miniterm, $(\bar{x}, S)$ respectively.Units (ms).

C	P_1	P_2	P_3	P_4	P_5
$(35549.7, 21.4)$	$(35547.1, 33.6)$	$(35549.6, 25.7)$	$(35549.2, 36.1)$	$(35548.5, 30.1)$	$(463314, 31.4)$
$(1,604 \cdot 10^{-6})$	$(1,945 \cdot 10^{-6})$	$(1,72 \cdot 10^{-5})$	$(1,101 \cdot 10^{-5})$	$(1,848 \cdot 10^{-6})$	$(1,67 \cdot 10^{-5})$

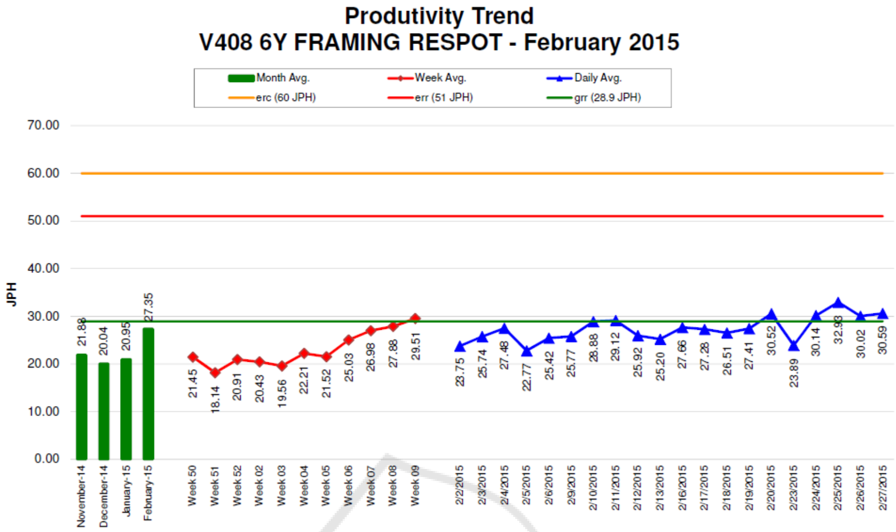

Figure 6: Jobs Per Hour produced in a real welding line VS idealized production rate. Note: ECR (engineering running capacity). ERR (engineering running rate). GRR (get ready requirement).

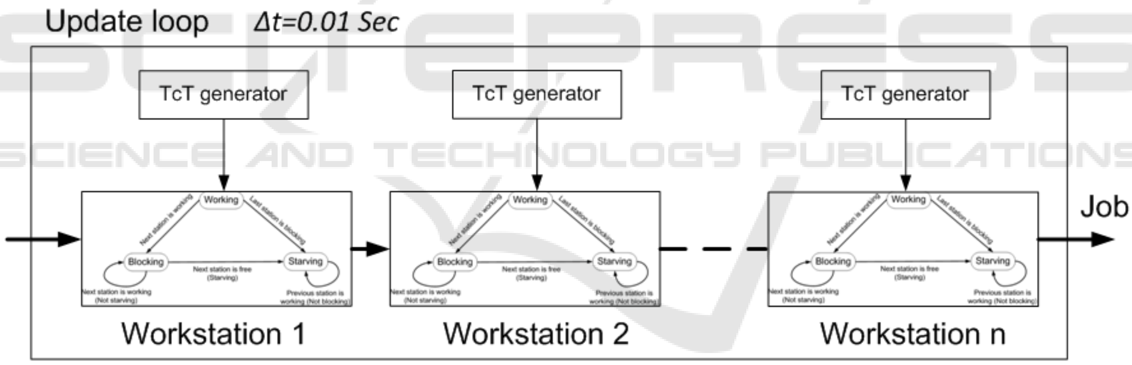

Figure 7: State machine workstation simulation.

5.1 Discussion

Through the simulation results obtained we can see how sensitive the production rate is to some small cycle time variations, in particular, mini-terms. Table 2 shows the maximum and minimum Jobs produced for each base time. If we compare the results with the simulated ERR, (51,1.05) JPH, there is a lot of jobs per hour lost.

The least impact is from pathology 3 and 5, just only a few jobs in a day. By contrast the greatest impact is for pathologies 1 and 2, where in the worst case more than 50 % of production can be lost. It is important to remark the dispersion of the results. In the worst case of pathology 2, the variance is 9.5, in JPH and 171 in JPD. These results are due to the Bowl Phenomenon effect that propagates the variability starting from the bottleneck and producing a multiplied effect, see (C.E.Lopez, 2014). The bowl phenomenon is the main responsible for the results, because, when the pathology has a similar variance than the ERR, the difference only depends on the mean value. For instance, Pathology 5 has a 30 % of mean time in the mini-term robot motion, compared with the mean value of ERR. However, if it has similar variance, it means that only the mean value affects the production rate. However, the results are very different when the variance is greater than the ERR. In this case, the welding line is completely unbalanced and the production rate turns unpredictable. The sim-

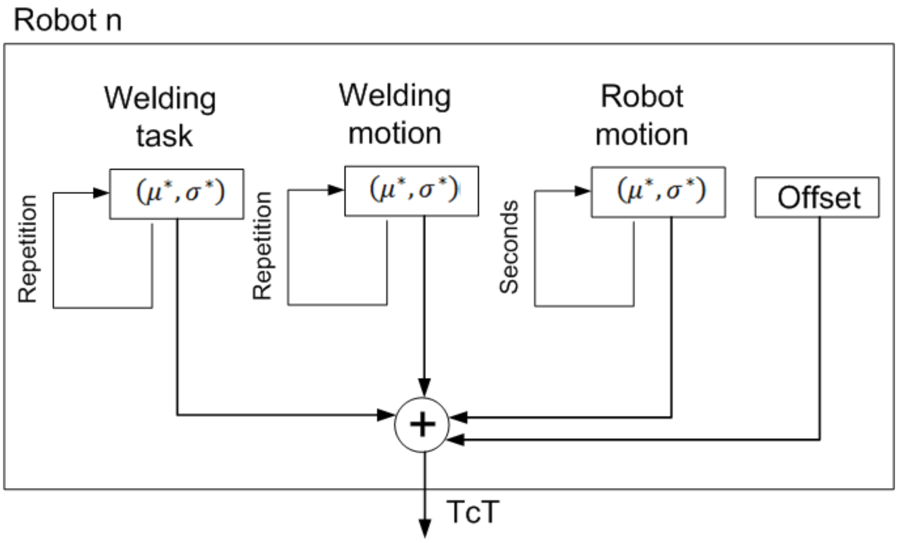

Figure 8: Cycle time computation for each robot/Welding unit.

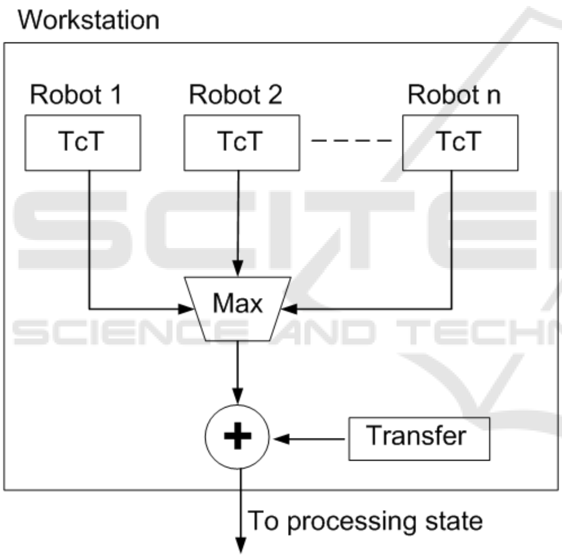

Figure 9: Cycle time computation for each Workstation.

ulation result demonstrates that the reason for the loss of jobs is the machine variability, and ERC cannot be achieved due to the mini-term and micro-term time deviation of each machine. For instance, if we replace the deviation of each mini-term in the case of "without pathology" for 0.01 sec, the simulation gives (57, 0.47) JPH, 4 Jobs below the ERC.

6 CONCLUSIONS AND FUTURE WORKS

This paper presents how the variability of a machine part can affect the production rate in a line. For this purpose, mini-term and micro-term cycle time subdivision is introduced. The present paper focuses its attention on a welding line located in a Ford Factory in Almussafes (Valencia). A welding station is isolated and tested for some particular pathology. The deterioration of a proportional valve, the cylinder, the transformer, the robot speed and the loss of pressure are tested in the range that the alarms and the maintenance workers cannot detect. The welding line is modelled and a simulation algorithm based on machine states is constructed. The experimental measurements are introduced in the algorithm and the effect in the production rate is tested. As a result, the pathologies with greater variability have a deep impact in the production rate mainly because of the bowl phenomenon effect. On the contrary, pathologies with low variability have a low effect in the production rate. The simulation algorithm allows us to demonstrate the reason for which the ERC cannot be achieved in a real production line, which is the ma-

Table 2: Simulation results when a single pathology occurs in a single welding station (μ,σ) JPH.

Pathology	Production Rate	Location (WS,Wu)
1	Max (35,3.39)	(1,4)
	Min (26,6.28)	(8,6)
2	Max (39,0.98)	(1,1)
	Min (24,9.53)	(7,5)
3	Max (51,1.06)	(1,1)
	Min (50,1.44)	(1,5)
4	Max (40,3.25)	(1,4)
	Min (34,7.01)	(7,5)
5	Max (51,1.11)	(1,4)
	Min (50,1.17)	(8,4)

chine time variability. If we replace the deviation of the mini-terms in the case of "without pathology" near to zero, the JPH are near to the ERC. The results presented in this study open new challenges and research work for the future. On the one hand, the watchdog agent that detects these anomalies in the production rate will be our immediate future work. Early detection of these pathologies will produce an increase in the throughput. On the other hand, a deep characterization of the machine part deterioration is required. Although manufactures have a threshold for the lifespan of the parts, however, for maintenance workers the evolution of the deterioration during the lifespan time could be crucial in the throughput of the line, as well as for the detection of pathologies with great variability, evidence is given on how the variability of machine parts can affect the throughput of an assembly line. It is important to state that the present study only takes into account one pathology in one welding unit and the others are without pathologies. It is likely that in a real welding line all the welding units have a percentage of deterioration.

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