Towards a Self-balancing Machine Velocity Production Line for Energy Saving

E. Garcia[1] and N. Montes[2]

[1]Ford Spain, Poligono Industrial Ford S/N, CP 46440, Almussafes, Valencia, Spain

[2]Department of Physics, Mathematics and Computing, University CEU Cardenal Herrera, CP: 46115, Alfara del Patriarca, Valencia, Spain

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Abstract: The present study analyzes how to re-balance a real world manufacturing line for energy saving by means of machine velocity reduction. Without loss of generality, the paper is focused in Industrial Robot (IR) lines where the velocity of each robot is properly tuned using a predictive control technique. It predicts the IR idle time for the next cycle based on the model line knowledge, the mini-term sub cycle time measurements and simulation techniques. The proposed predictive control technique is tested off-line, using a real world welding line model located at Factory Ford, Almussafes (Valencia). Also an estimation of the stored energy is computed by means of an experimental test developed in a real welding unit. A discussion on how to implement it in a real line is done at the end of the paper.

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 is suitable for onward consumption; or components are assembled to make a finished article. Because of the high investment and running costs involved, the design of such lines is of considerable importance, (O.Battaa, 2013). There are a large number of crucial decisions to be made in flow line design 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.Battaa, 2013). The last and crucial step in the process design is the line balancing, (O.Battaa, 2013). Here tasks are assigned to the workstations and resources that will be employed on the line. Due to the relevance of this task, a large number of researchers have been working on this topic, (O.Battaa, 2013). 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.Battaa, 2013).

Recently, the pressure to reduce energy consumption in the industry is growing due to increasing costs of electricity and resources. The motor vehicle industry alone in the U.S. spends about 3.6 billion Dollars on energy annually, (C.Galitsky, 2008). Therefore, the energy saving goal is a key point for the industry and also for the governments as the European Union, (Comission, 2016). For that reason, in the production line balancing problem, energy saving is a crucial goal recently. Primary research efforts on manufacturing energy savings have focused on developing individual energy efficient machines. (G.Mouzon, 2008b), (G.Mouzon, 2008a), pointed out that if instead of leaving the non-bottleneck machines idle, they were turned off until needed, then 80% savings on total energy consumed on idle, start up, and shut down could be achieved. However, there are significant amounts of energy required for machine startup. This suggests that energy saving efforts focusing solely on updating individual machines or processes may be missing a significant, and perhaps a bigger, opportunity i.e., system-level changes and coordinated control (Q.Chang, 2013). It is due to production lines are a complex dynamic system with interdependence among different machines and unscheduled events like downtimes, breakdown and other random disturbances, (Q.Chang, 2013). Most current manufacturing execution systems (MES) have no module or function to deal with energy management during operation, which means that a huge amount of energy is wasted during the machine block-

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age and starvation without production, making the energy efficiency really low. Leaving a non-bottleneck machine idle due to lack of multiple operation states setting seems to be a routine and regular operating practice in the industry. In (Z.Sun, 2011) considers that modern machines or motors systems have multiple adjustable power states instead of traditional ON, OFF states. The power state is maintained on the ON level when it is processing parts; while the power hibernation mode may be triggered when it is detected to be starved or blocked. In (L.Li, 2013), The interactions between the adopted energy control decisions and system state evolutions are modelled by Markov decision process (MDP).The decision is to adjust the energy mode for each machine according to not only current states but also possible evolutions of system states in the future. In (Z.Zhou, 2013), a heuristic method considering throughput bottleneck detection for real time electricity demand response under the production constraint is introduced.

1.1 Energy Saving in Industrial Robots

One of the areas in which a significant amount of energy can be saved in manufacturing process is in industrial robots (IR). For example, the energy needed during the production of cars is approximately 8%, (D.Meike, 2011b). Therefore, the primary goal of the optimization is to minimize the energy consumption of a robotic cell for a given production rate by changing the robot speeds, positions, order the operations and applying the robot power saving modes, (L.Bukata, 2016). However, energy consumption reduction for IR can be achieved at different stages of a manufacturing systems' developments: During production planning, commissioning process, or at optimization stages, see (P.Matthias, 2015). At the production planning stage, engineers are more flexible with optimizing the process and defining a strategy for reducing energy consumption, for example, by optimizing IR operation schedule, (D.Meike, 2011b) or by optimizing IR parameters, like the speed and acceleration of the robots, (D.Meike, 2011a), (A.Kovetski, 2008). At the commissioning stage, reducing energy consumption can be conducted by eliminating waiting and iddle time of IR but manufacturing productivity must be considered. At the optimization stage, the engineers cannot change the hardware apparatus or the production rate. Therefore, the energy reduction must be done by releasing the actuator brake earlier and implementing optimal trajectories using time-scaling methods, (D.Meike, 2014), (P.Matthias, 2015), (S.Riazi, 2016).

1.2 Real World Line Balancing Problems

Although many solutions for reducing the energy consumption of IR have been provided, majority of them are focused in primary stages. Optimizing the motion planning of IR can reduce energy consumption but less interesting for practical point of view and only effective for an IR manufacturers, (P.Matthias, 2015). Optimizing the operating parameters is a relatively new method but is only effective in the production planning stage, while the productivity rate at the manufacturing system is planned, (P.Matthias, 2015). In the end, an expert team designs the line, based on all of these parameters and defines the maximum production rate, adjust the IR parameters, program the trajectories, schedule the tasks, etc. However, during the lifespan of the line, which could be decades, the line suffers a lot of changes due to market demand with new products or models manufactured in the same line, new technologies like for instance a new robot arm that can run more faster than when the line was designed, deteriorating systems that affect the throughput and also produce a dynamic bottleneck behaviour, etc, see (E.Garcia, 2016).

Many of the Operational Research approaches as well as energy saving strategies implicity assume that the problem to be solved involves a new, yet-to-be build assembly line or yet-to-be-build-factory. However, the vast majority of real-world line balancing tasks involve existing lines, (E.Falkenauer, 2005). In fact, the target line tipically needs to be re-balanced rather than balanced.

1.3 Previous Works

In (E.Falkenauer, 2005) was defined that each workstation have its own identity, meaning that the workstations in the real world are indeed not identical. The same concept was deep analyzed in our previous works where not only the workstations are not identical, but also the components that form each machine are different and do not have the same behaviour in each cycle time repetition.The literature classify the data used in the production line analysis into *long-term* and *short-term*. *Long-term* is mainly used for process planning, while *short-term* focuses primarily on process control. In (E.Garcia, 2016), *short-term* was divided into two new terms, *mini-terms* and *micro-terms*, see Figure 1.

A *mini-term* may be defined as a part of the machine, in a policy preventive maintenance or a breakdown, which could be replaced in an easy and faster maneuver than other machine sub-division. A *micro-*

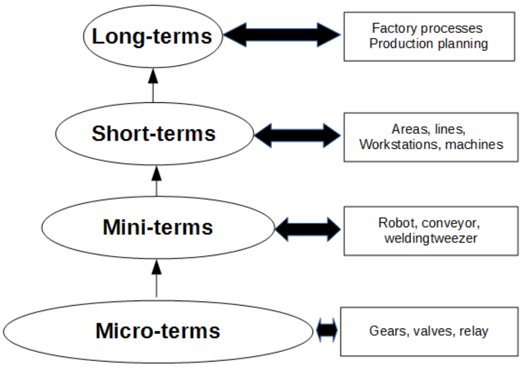

Figure 1: From micro-term to Long-term.

term is defined as each of the *mini-term* sub-division. It could be divided to the level of depth that the user requires. Therefore, the probabilistic cycle time of each machine or station is a concatenation of the probabilistic *mini-terms* and *micro-terms* times where each could have a different probability distribution.

In (E.Garcia, 2016), (E.Garcia, 2017) was proposed an experimental setup to measure the most common *mini-terms* of a welding unit. In this case, the welding unit is divided into three *mini-term*s, the motion of the robot arm, the motion of the welding clamp and the welding task, see Table 1. The tests developed in (E.Garcia, 2016), (E.Garcia, 2017), allow us to measure the sub-cycle times for each *mini-term* at the start (Table 1,test 0) and near to the end of the lifetime of some particular machine component. The deteriorated components were selected at the welding line at Ford Motor Factory located at Almussafes (Valencia) with some particular pathologies which are not detectable by the machine control systems or by the maintenance workers. The pathologies are; the stiffness of a proportional valve (Table 1,test 1), the pneumatic cylinder wear, galling or communication inside the stem (Table 1,test 2), the loss of the wire insulation in a transformer (Table 1,test 3), the loss of pressure in a pneumatic circuit (below the alarm value) (Table 1,test4) and the loss of the robot speed (Table 1,test5).

Test 0 demonstrates that the line components have its own identity and do not have the same behaviour in each repetition. Moreover, the line components, cylinders, transformers, etc, are deteriorated during their lifetime. Therefore, the probabilities, mean and variance changes, modifying the productivity rate and defining a new alternative for predictive maintenance, see (E.Garcia, 2016), (E.Garcia, 2018).

Table 1: *mini-terms* for a welding unit (μ,σ) with (Test 0) and without deterioration (Test 1-5).

Test	Robot arm	Clamp	
	Motion	Motion	Welding
0	(1,0.11)	(0.42,0.47)	(1.44,0.84)
1	(1,0.18)	(0.43,0.51)	(4.05,10.9)
2	(1,0.13)	(1.41,3.42)	(1.14,5.99)
3	(1,0.19)	(0.46,0.54)	(1.76,0.91)
4	(1,0.16)	(1.56,3.74)	(1.29,5.08)
5	(1.3,0.16)	(0.41,0.46)	(1.45,0.85)

2 NUMERICAL CASE EXAMPLE

2.1 Welding Line Case

In order to test and illustrate our proposal, a real welding line located at Ford Almussafes (Valencia) is used, see Figure 2. In a real welding line like this, there are welding workstations where, each one has welding stations working in parallel and sometimes in serial. Each welding station makes some welding points in the same cycle time. It is possible to find 1,2,4 or at least 6 welding station in the same workstation, where each one makes up to 19 welding points. In our particular case, our welding line has 8 workstations where workstation 1,5 and 6 have 4 welding units,workstations 2,4,7 and 8 have 6 welding stations and workstation 3 has 1 welding unit, see Figure 3. 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 (Jobs Per Hour). However, the plant engineers have another maximum running capacity, that is the ERR (engineering running rate), in this case defined in 51 JPH. Nowadays, this line welds 68 different models and variants. Different car models with 3,5 doors with or without solar roof, etc. Obviously, from 1980 to today, the line suffers a lot of changes and updates, new models and variants are appear and old models and variants disappeared, most advanced robot arms and welding units are introduced, etc. Therefore, the line is re-balanced, if it is possible, when new update occurs.

Figure 2: Welding line at Ford Almussafes (Valencia).

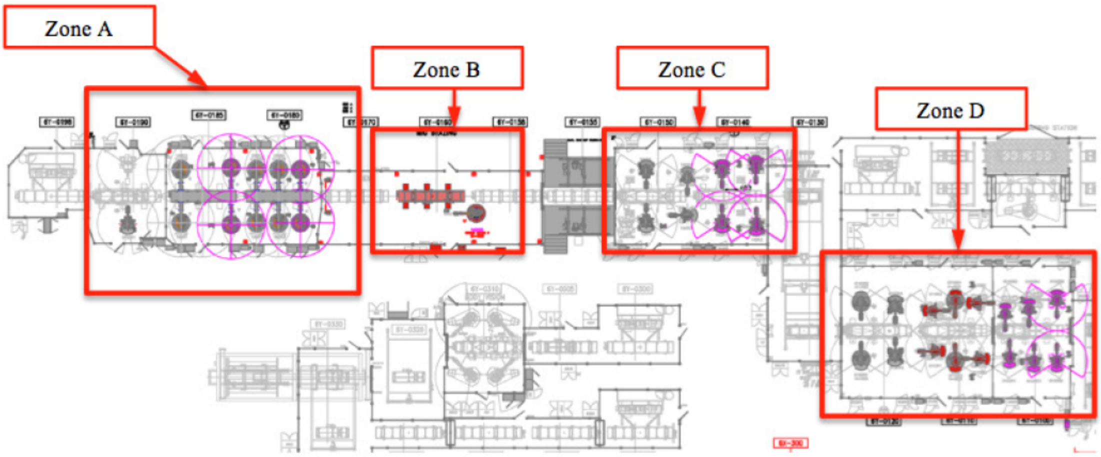

Figure 3: Welding line layout.

2.2 Welding Line Modelling

The welding line was modeled taking into account the *mini-terms* subdivision. that is, the motion of the robot arm (the time that the robot is in movement), and the number of welding point for all the 68 different models and variants, see (E.Garcia, 2016), Anex 4. Also in (E.Garcia, 2016), Anex 4, there is the offset, time that a particular robot is awaiting for another robot in the same workstation and the transfer time, the required time to move the car body to the next workstation, (12 seconds). With this model and using a computer simulation explained below, the productivity rate was re-computed in, (E.Garcia, 2016) ,(E.Garcia, 2017), taking into account the variability and the production schedule.

2.3 Welding Line Simulation

The common way to simulate a production line is to use a simplified machine state, see Figure 4, with three possible states, *Working*, *Starving* and *Blocking*.

First of all, let us to define a serial production line with three stations, *a*,*b* and *c*, that are chained in this order. If station *b* is in *Working* state and the work is finished, it checks station *c*, if it is in *Starving* state, the finished part of product is delivered to it and station *b* is free to receive another job. If station *c* is in *Working* state when station *b* finishes its work, station *b* changes its state to *Blocking*, blocking itself until station *c* is free. If station *b* is free to receive another part, it checks the previous station. If station *a* is in *Working* state, station *b* changes to *Starving* state waiting until station *a* has a part to work on. If station *a* is in *Blocking* state, station *b* receives the part so, the state of station *b* changes to *Working* and the state of station *a* changes to *Starving*. When simulation starts, every station state is set to *Starving*, until the first station is set to *Working* state. The simulation loop runs at predefined step time (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.

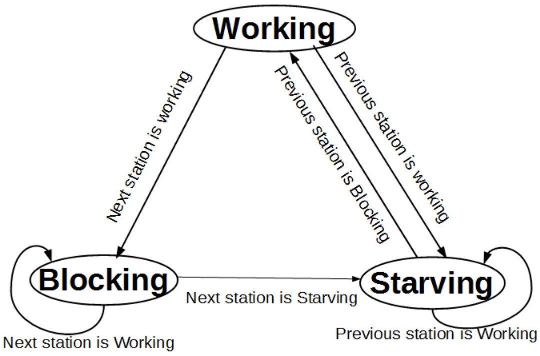

Figure 4: Simplified state machine.

In order to simulate the welding line, a chain state machine simulator is developed, see Figure 6. The loop is updated with an incremental time of 0.01 seconds. When the cycle time is finished in a particular workstation, a new cycle time is computed for the next part, taking into account the car model that will be manufacture in the next cycle. It is important to point out that there are different *mini-terms* and repetitions of each one for each particular car model developed in a welding line, see figure 5.

In the simulated welding line, a job is always performed in the first workstation, so that the *blocking* state cannot be reached in the first station. In addition, all the finished jobs in the last workstation are retired, so that the *Starving* state cannot be reached in the last workstation. The loop starts with all the stations in the *Blocking* state.

The cycle time for each workstation is the max-

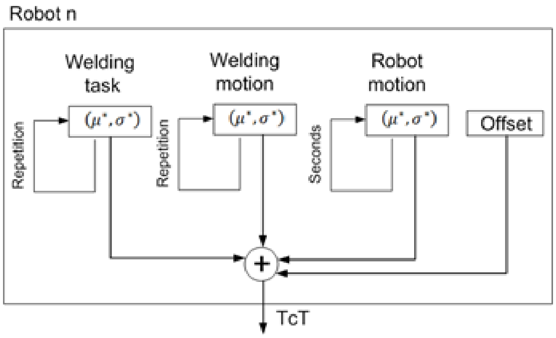

Figure 5: Cycle time computation for each welding unit.

imum cycle time of each welding station that works in parallel, indicating the slower welding unit and the bottleneck in a particular workstation.

3 PREDICTIVE CONTROLLING TECHNIQUE FOR ENERGY SAVING

In order to test the energy saving algorithm proposed below, a model, or variant 12 for the (E.Garcia, 2016), anex 4 is selected. The values of this model are shown also in the Table 3 of the present paper. If a simulation is run supposing that the welding line only produces this model, and the *mini-terms* are without deterioration (Table 1,test 0) the production rate is $(45.0, 1.07)$, mean and variance respectively. The simulation also computes the starving and blocking times, that are shown in figure 7. As can we see, workstation 4 is the bottleneck workstation, mainly because, blocking and starving time are produced at the previous and later workstations respectively.

Based on blocking and starving times, let us to define idle time as;

$$Id_k^W = Max(S_k^W, B_k^W) \tag{1}$$

where Id_k^W is the idle time for the workstation W that manufactured the part in the k instant of time. S_k^W, B_k^W are the starving and blocking time the workstation W that manufactured the part in the k instant of time. The equation 2 shows how to estimate the minimum velocity at which each robot could run without loss of production rate, that is;

$$\%v_k^{W,R} = \frac{mR_{Zoh}^{W,R}}{mR_{Zoh}^{W,R} + Off^{W,R} + Id_{Zoh}^{W}} \tag{2}$$

where $\%v_k^{W,R}$ is the percentage velocity of the robot R in the workstation W that can be applied for the part manufactured at the time instant k, $Off^{W,R}$ is the offset for the robot R at workstation W. $mR_{Zoh}^{W,R}$ is an estimation of the *mini-term* robot R at workstation W. This estimation is done by means of Zoh (Zero order hold) technique using the next equation;

$$mR_{Zoh}^{W,R} = mR_{k-1}^{W,R} \tag{3}$$

Id_{Zoh}^W is an idle time estimation for the part that will be manufactured at the time instant k. This estimation is done by means of a computer simulation technique using the estimated *mini-terms*, that is;

$$mCm_{Zoh}^{W,R} = mCm_{k-1}^{W,R}, mCw_{Zoh}^{W,R} = mCw_{k-1}^{W,R}, \tag{4}$$

where $mCm_{Zoh}^{W,R}$ and $mCw_{Zoh}^{W,R}$ are estimations of the *mini-term* clamp for a robot R at workstation W. Also the velocity reduction applied for the previous part, $k-1$, is taken into account. An schema of the proposed strategy is shown in figure 8.

Table 2 shows the velocity percentages for each robot at each workstation. With these velocities, the line is re-balanced and the starving and blocking time are nearly to zero, see figure 9, maintaining the production rate,$(45.0, 1.07)$.

Table 2: Velocity percentages for each robot.

W/R	1	2	3	4	5	6
1	52	52			55	56
2	78	79	71	73	85	66
3			23			
4	0	0	0	0	0	0
5	80	81	85	85		
6	80	81	66	62		
7	75	74	75	75	75	75
8	84	84	80	79	83	83

3.1 Welding Line Energy Saving Estimation

In order to estimate the energy saved with this strategy, the energy consumed for a particular welding unit at different velocities was done. This experimental test isolates one welding unit, see Figure 10, where a current clamp is located at the wire that supplies energy to the welding unit. The test uses one of the common trajectory planning programs used in the welding line. Therefore, the energy consumed by the welding at different velocities is obtained, see Figure 11.

With this curve, the estimated energy consumed if all the welding units work at maximum velocity speed is 7008 Kwh. Applying the velocity reduction, the estimated energy consumed is 3007 Kwh.

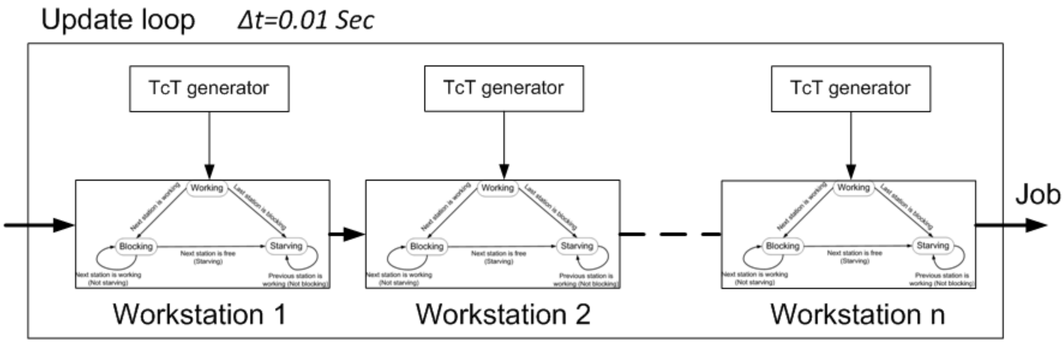

Figure 6: Welding line simulation.

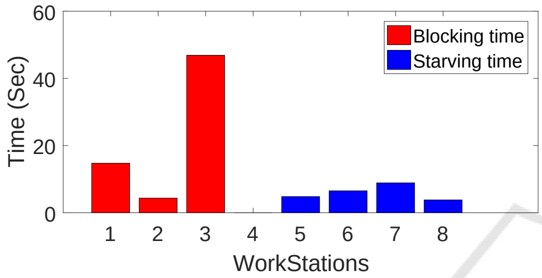

Figure 7: Starving and blocking time before velocity reduction.

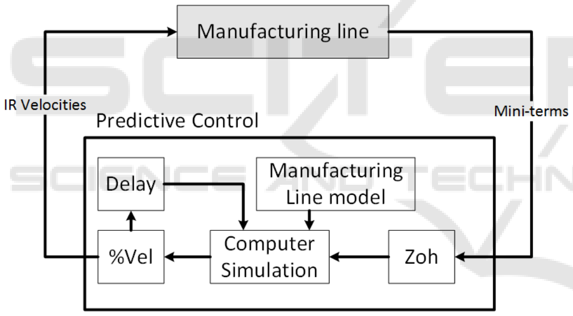

Figure 8: Control loop schema.

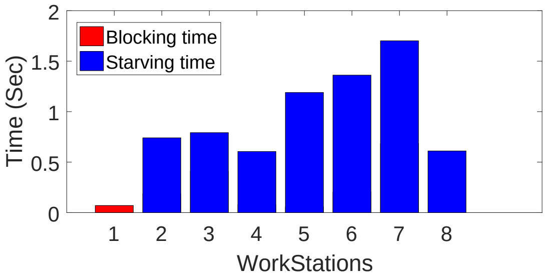

Figure 9: Starving and blocking time after velocity reduction.

4 DISCUSSION. TOWARDS A REAL-TIME ENERGY SAVING SYSTEM FOR INDUSTRY 4.0

The present paper treats to define how to develop a real-time control strategy to re-balance manufactur-

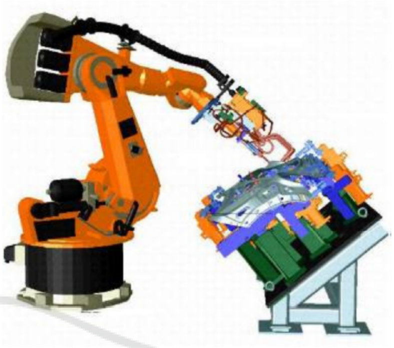

Figure 10: Isolated welding unit.

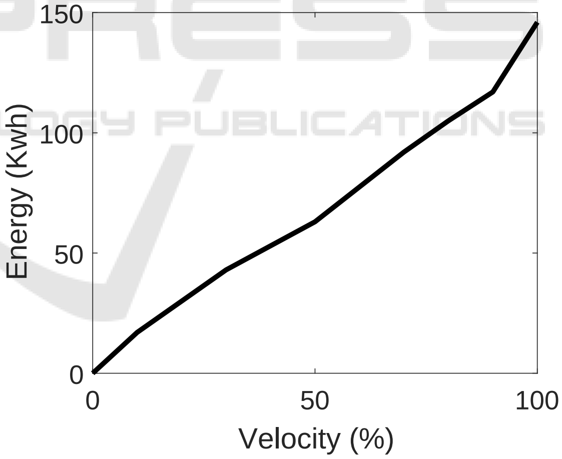

Figure 11: Velocity percentage VS energy in a real welding unit.

ing lines by means of IR velocity reduction. The first affair to discuss is the parameter used to re-balance. As can be explained in the introduction, the vast majority of the techniques proposed are only valid for a new line, not an existing one. Changing machine parameters in real-time could be a solution and, the velocity and acceleration could be the better one. It is due to the kinetic energy is the energy used in manufacturing plants because the parts are moved parallel to the floor. In particular for automotive industry,

Table 3: *mini-terms* for a model 12.

		Robot 1	Robot 2	Robot 3	Robot 4	Robot 5	Robot 6
Workstation 1	Robot motion (Sec)	14	13.26	20.84		16.52	13.72
	Welding motion (Units)	9	9	6	6	18	18
	Welding task (Units)	9	9	6	6	18	18
	Offset(Sec)	0	11	11	0	0	0
Workstation 2	Robot motion (Sec)	24.76	21.26	—	—	9.52	11.52
	Welding motion (Units)	9	9	—	—	18	18
	Welding task (Units)	9	9	—	—	18	18
	Offset(Sec)	0	4	—	—	0	0
Workstation 3	Robot motion (Sec)	—	—	19.56	—	—	
	Welding motion (Units)	—	—	9	—	—	—
	Welding task (Units)	—	—	9	—	—	—
	Offset(Sec)	—	—	0	—	—	—
Workstation 4	Robot motion (Sec)	13.96	16.54	16.54	17.4	—	—
	Welding motion (Units)	14	11	11	10	—	—
	Welding task (Units)	14	11	11	10	—	—
	Offset(Sec)	0	0	0	6	—	—
Workstation 5	Robot motion (Sec)	16.26	15.12	20.68	21.4	—	—
	Welding motion (Units)	9	8	12	10	—	—
	Welding task (Units)	9	8	12	10	—	—
	Offset(Sec)	0	2	0	0	—	—
Workstation 6	Robot motion (Sec)	20.26	11.02	14.12	11.34	—	—
	Welding motion (Units)	9	18	8	6	—	—
	Welding task (Units)	9	18	8	6	—	—
	Offset(Sec)	0	0	0	0	—	—
Workstation 7	Robot motion (Sec)	11.66	10.10	12.38	8.52	7.52	19.26
	Welding motion (Units)	19	15	17	18	18	9
	Welding task (Units)	19	15	17	18	18	9
	Offset(Sec)	0	0	0	0	0	0
Workstation 8	Robot motion (Sec)	12.24	13.10	12.38	14.10	13.96	15.68
	Welding motion (Units)	16	15	17	15	14	12
	Welding task (Units)	16	15	17	15	14	12
	Offset(Sec)	0	0	0	0	0	0

huge masses as body car are moved, acting as an scaling factor. In addition to that, all the Industrial robots manufactures provides a velocity control parameter for a predefined program and can be controlled using an external input, making easily and cheap the control system. The second affair is if the IR velocity reduction is the best choice for energy saving. For instance, in the welding line analyzed here, it is not clear if is better to reduce IR velocities or reduce the velocity conveyor. The first one moves welding units at high speed, low weight, but the second one moves the body car, high weight.

The third affair is how to compute the velocity reduction. The solution proposed in the present paper is only tested for an isolated manufacturing line, welding line, that produce a single model. Real world shows that the line produce 68 different models with a predefined production schedule.

To end up, A Real-time energy saving system that re-balance the velocity or acceleration needs Industry 4.0. Real world lines have their own entity, even each *mini-term*. Real-time monitorization, not only for the mini-terms but also breakdowns and other real world facts must be taken into account to re-balance the velocity successfully without reduce the production rate.

5 CONCLUSIONS AND FUTURE WORKS

The present study shows, for the first time, a control technique to re-balance a manufacturing line for energy saving. The re-balance is done by means of Industrial Robots velocity reduction. A predictive control technique is used to estimate it by means of Zero order hold (Zoh) technique for the real-time *mini-term* measurements. A computer simulation give us an estimation of the idle time for the part that will be produce in the next cycle time.

Future works are focused in three main branches that we are working in parallel. The first one is to deeply analyze all the systems that acts in a manufacturing automotive industry to determine which is the better choice to reduce the velocity, based on the energy saving point of view. The second one is to improve the technique proposed here for multi-model lines. In that case, the predictive control must take into account the production schedule for the velocity estimation reduction. The last one is to implement a real setup to test on-line the schema proposed in Figure 8. In that sense, a real line that produce a single model could be used to test the efficiency of the technique proposed in the present paper.

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