Autonomous energy-aware production systems control

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Abstract: Energy and resource efficiency has recently become one of the most relevant topics of research in manufacturing, both as industry accounts for a major part of the world energy consumption and in the context of the increasing attention to the need of sustainable development at planetary level. This work aims at paving the way to the development of novel energy-aware control policies of production systems, by means of autonomous decisions about their states in terms of production and energy consumption, exploiting the possibilities given by the new ICT technologies, such as Internet of Things and cloud computing, which allow seamless information sharing among the machines through an appropriate and standardized ICT infrastructure. The energy saving control approach investigated in this work exploits the current trend in research to reduce the idle time of machines in favor of stand-by states, obtaining significant savings in terms of energy, by allowing novel solutions for decentralized control. The proposed control enables the production machines to autonomously share with and process the information of the other machines in the system to decide in real-time their specific energy behaviour, even postponing processing if that is possible. The approach adopted includes conceptual development of the dynamic behaviour models of the system and the proposed policies, then their deployment in an application scenario taken by actual industry cases and data, enabling study of the performance of the system with a detailed design of experiments. The proposed approach represents a significant contribution to the state of the art, as the proposed energy-aware control enables decisions based on real-time information instead of statistically-based forecasts of part arrival rates, as in the previous literature; furthermore the approach is of relevant value for the practitioner, especially as it paves the way to an operationalization to the vision of Cyber-Physical Systems and Industry 4.0.

Keywords: energy efficient manufacturing, energy aware machine control, sustainable manufacturing, cyber physical production systems, Industry 4.0

1. Introduction

Energy and resource efficiency has recently become one of the most relevant topics of research in manufacturing, both as industry accounts for a major part of the world energy consumption, as well in the context of the increasing attention to the need of sustainable development at planetary level.

The article proposes a novel approach for energy efficient line control, exploiting the potential of the recent developments of ICT systems, in particular proposing energy aware control of a serial production line.

The article is organized as follows. Section 2 reviews the relevant literature, Section 3 presents the aims and objectives of the research and how these were addressed, Section 4 both acts as presentation and explanation of the article key findings: conceptual model, energy saving policy and enabling ICT architecture. Section 5 presents the system of which we explored the behaviour, with a discret event simulation model purposefully developed by enhancing with customized code the fuctionality of an established off-the-shelf simulation tool, and which we validated and experimented, including a detailed and quantitative discussion of the experiment findings. Finally, Section 6 focuses on conclusions and highlights the importance of the research and depicts possible future steps.

2. Related work

Production planning and control of production systems has been extensively studied over the years, historically with focus on optimization of manufacturing material flow performance, such as minimizing make-span or optimizing throughput. Only recently the research has addressed the topic of energy and resource consumption in manufacturing. In this context, the open flow line with serial machines, although extensively studied in the literature, still lacks some points of study, especially from the point of view of energy efficiency. In particular, most of the models in the literature focus on the behaviour of a single machine and do not consider the whole line with respect to energy consumption.

Here it is interesting to note that the most interesting contributions by which authors have introduced the study of energy-aware switching-off policies for a flow-line (e.g., Mouzon 2007, Frigerio and Matta 2014, Frigerio and Matta 2015); nonetheless, even if these authors have put the basis for a better comprehension of the potential savings deriving from application of energy control policies, the existing models are still incomplete, most of all because they do not consider some important elements affecting machines, such as failures.

Furthermore the previous work, though the validity of their rules, they are still based on statistical models, with stochastic inter-arrival times and job arrivals, which do not take into account the fact that the new ICT communication and monitoring technologies can provide real-time data, exploiting for instance Internet of Things and Cloud Computing capabilities. These new ICT developments seem very promising, despite the current lack of interoperability between the different control levels of a factory (SCADA, MES and ERP systems); in fact, most likely, in the current vision of Cyber Physical production systems, recently embraced by industry, academia, research and public bodies, the swift technology innovation will soon overcome many of the constraints towards the vision of Industry 4.0.

3. Aims and research approach

The research carried out for this paper aims at finding out methods for optimizing manufacturing systems (in this case serial lines) taking into account both traditional performance, such as throughput and flow time, together with energy and resource efficiency, with a broad viewpoint.

As pointed out previously concerning the complexity of the models, stochastic and with dynamical propagation of disturbances (that is, variations in production time, in availability of machines etc.) we chose the simulation as main tool for our experiments.

The research carried out for this paper can be broadly divided in three phases: i) development of conceptual models (analytical and dynamic) of the components of the system studied including potentially promising energy saving control policies, ii) simulation of the whole system and iii) identification of optimization configurations, followed by result confirmation by application to actual scenarios.

4. Research findings

4.1 Conceptual model

Our conceptual model of the system under investigation, a serial line, includes the following elements: production stations (from now on, machines), buffers, physical flow of the processed parts and information flow, that is data exchange among the machines (see figure 1). Main system parameters are number of machines and buffers, machine deterministic processing times, finite buffers, unreliable machines.

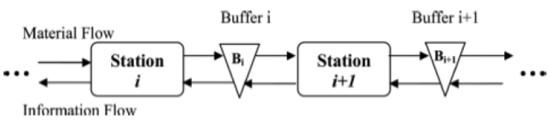

Figure 1: serial line system

Each machine can be modelled with i) an automata or state machine describing its working cycle and ii) an 'energy and resource profile'.

The automata describes the evolution of the working cycle, from *ready* to *processing* and back to *ready*, including also the transitions needed to configure the machines to *ready* from the *off-state*. A specific state, namely, the *stand-by* state, has been identified by the machine builder as a controllable 'low consumption' state, in comparison to the *ready* state, but has faster transitions to/from *ready* state in comparison to *off*.

The energy and resource profile, previously proposed by Fantini et al. (Fantini et al., 2014) and tested by Palasciano et al. (Palasciano et al. 2016), identifies, for each state of the working cycle, the average energy and resource consumption values needed, in this case, power consumption (an example is presented in Table 1).

Table 1: machine energy profile (example)

State	Time (sec)	Power (kW)
Off	N/A	0
Ready	N/A	$P_{ready} = 4$
Processing	PT_{part}	$Pp_{Processing} = 8$
Stand-by	N/A	$P_{standby} = 2$
Power down	T_{pd}=10 sec	$P_{powerdown} = \ldots$
Ramp up	$T_{ru}=\ldots$	$P_{rampup} = \ldots$

Finally, each machine, besides the standard machine control capabilities provided by automation systems (PLC), must be provided with local information processing and communication capabilities which allow the machine to a) publish information concerning its state and, if in processing state, the forecasted end of processing time and receive the information from the other machines and buffers (in this case, upstream and down stream) and b) autonomously set up the standby if a specific energy saving rule can be triggered.

This approach operationalizes the principles of Cyber Physical Systems into our serial line control, with the specific objective of optimizing the energy consumption.

With reference to the 5C CPS reference architecture (Lee et al., 2015), our approach allows the identification of a cyber 'double' (at level 3 of the 5C architecture) of each machine, which can be shared in the production network, in this case enabling autonomous real time control, which, at level 5 of the 5C architecture, means self-configuration (*stand-by* state is triggered by each machine autonomously).

4.2 An autonomous energy saving policy

According to the approach described in section 3, the authors have started development of potential effective energy saving policies, which have been assessed by simulation experiments. We recount in this paper one of the most promising energy saving policy which has been developed and experimented by deployment of a simulation model in Plant Simulation production systems graphich environment (Siemens 2016), extended with personalized SimTalk code to enable real time control by using the developed energy saving policy.

The energy saving policy object of this paper, namely Current Job Aware – from now on, CJA (Rapuzzi, 2015), has been inspired by previous work (Mouzon, 2007) and is built on rules that are triggered by events such as change of state in the input (entry of a part to be processed) and in the system (such as end of processing in machine *i* or failure of machine *j*.

It is not in the scope of this paper to explore in detail the design, implementation and experimentation recounted in the mentioned work; we would like to summarize here the main elements of the research done:

- information exchange among machines;
- local energy saving decision policies.

Information exchange enacted by each machine allows them to estimate the time when the part to be worked will arrive (that part is called Current_job i) and therefore, based on the energy profile information of the Processing Time for that part, when the part will exit the system. As the system under investigation include unreliable machines, if a machine j fails, this event triggers information propagation for updating all the entry and exit times in downstream machines.

The energy saving policy CJA is inspired by the rules evidenced by Mouzon (Mouzon et al., 2007), which defines Threshold Time (TT) as the minimum time value that 1) allows switching the machine in *stand-by* and power it up and 2) makes it convenient to put the machine in *stand-by* as the energy consumed in *ready* state is more than the energy consumed in the same time period in the stand-by state, considering as well the needed power-down and ramp-up energy. According to the performed experiments, the CJA policy allows interesting energy savings between 20% and 40% in comparison to the baseline without energy control (see section 5 for more details).

We describe briefly in the following sections the main elements of the energy saving policy, that is the policies applied when a new part enrty into the system and when a generic machine *i* ends processing and then we describe the application of the CJA policy on a serial system, studied with simulation approach.

4.2.1 Entry of new part into the system

When a new part k enters the system, it becomes the processing candidate of the first machine in the line. If the first machine has no Current_job already, that is, there is no part upstream, then the new part becomes Current_job of the first machine. The same decision criteria is applied to all the machines in the line, up to the last one, so that each machine has a Current_job identified. For instance, if there is no part in the serial line, when the new part arrives, it becomes Current_job of all machines.

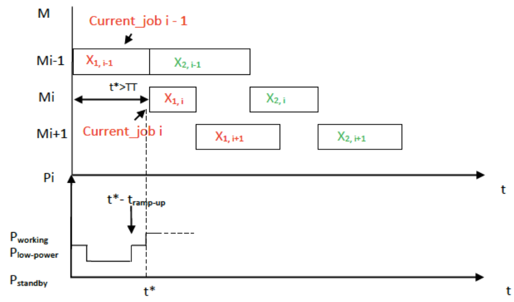

Figure 2: example of CJA policy (Rapuzzi, 2015)

4.2.2 Machine *i* ends processing

When machine *i* ends processing, it can take the decision to remain *ready* or to go in *stand-by*: for this, there are different situations to be checked out:

If there is a part in buffer *i-1*, the upstream buffer, that part is the Current_job *i,* and machine *i* stays ready to start processing

Otherwise, with no piece in the buffer *i-1,* machine *i* identifies its Current_job: there are two possible cases:

I) if there is no current_job *i* defined, that means that there is no current_job for upstream machine *i-1,* therefore machine I can go in stand-by;

II) if Current_job of machine i-1 is defined, then machine i checks exit time of Current_job i-1, comparing it to current time: if the difference is more than the previously defined Threshold Time TT, then machine i goes stand-by, otherwise machine i stays ready as it is not feasible or convenient to go back to ready state.

Additionally, when a machine *i* goes *stand-by*, a timer is automatically set to activate ramp-up transition Tru = Y sec before t*, the arrival of the Current_job.

Figure 2 shows an example of CJA policy application. It should be noted then that by enacting the CJA control policy, the overal makespan performance is not changed, as the energy saving policy is activated only to transform a time slot that otherwise the machine would have spent in ready state (without processing) into a stand-by state. Simtalk code for CJA policy is presented in Appendix A.

4.3 ICT architecture

The energy saving policy described in the previous subsections can be applied only if it is supported by a proper ICT structure that allows not only local data acquisition and processing, but also interoperable data communication among the different machines in the serial line, which might as well rely on different communication systems, being built by different machine builders. A possible ICT reference architecture which supports these requirements has been proposed by the EU project BEinCPPS (BEinCPPS, 2016) and is summarized in Figure 3.

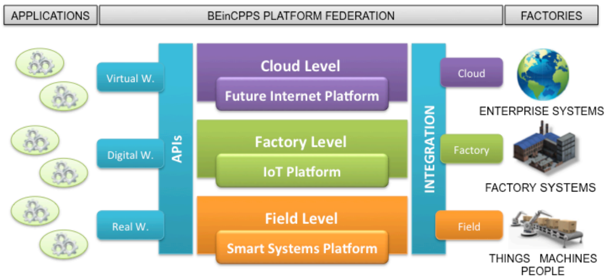

Figure 3: BEinCPPS architecture (BEinCPPS, 2016)

The BEinCPPS architecture, a platform based mainly on open source tools, allows connection of production systems belonging to different functional levels, starting from machines and people on the shop-floor (Field level) up to the technical and business users at higher level in the factory, and in the cloud at enterprise level.

Specifically, the functionalities required by the solution depicted in this work are delivered by the lowest levels. At the Field level we have people and hardware/software artifacts, in particular Embedded Systems (for field computation) and Real-Time Networks (for field communication). At the next level, the Factory level, the BEinCPPS architecture provides the Interoperability/Management and Information Bus layers, which create access paths to the heterogeneous environment of the shop-floor. The Interoperability/Management layer provides adapters supporting the most popular communication protocols for IoT and industrial automation – namely OASIS, MQTT and OPC UA, while devices and embedded systems are integrated with a two-sided Information Bus.

5. Application and simulation experimentation

We applied the proposed energy saving policy CJA to a serial line system made up with four machines (M1-M4) and four buffers (B0-B3) and deployed it in Siemens Plant Simulation V13 discrete event simulator in order to explore the performance of the policy in terms of energy consumption and overall production rate in different configurations (see figure 4).

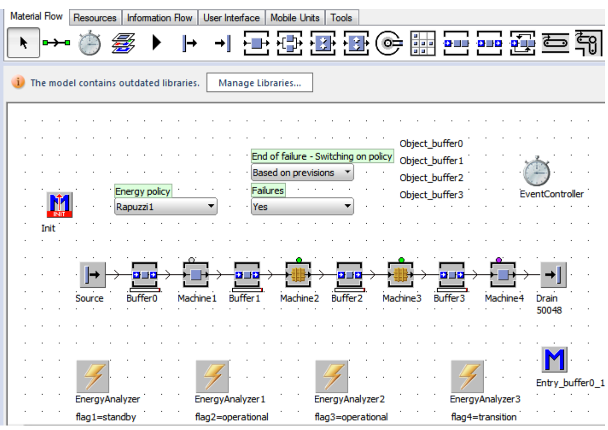

Figure 4: Plant Simulation V13 model (Rapuzzi, 2015)

Accordingly, our simulation model has been prepared in order to run with different configuration parameters, specifically with different interarrival time (IAT) of the parts to be processed and different threshold time (TT) and other parameters. We recount in this paper the results of the first experiments, based on a Design of Experiments plan which included a first validation of our model against previous work (see section 5.1) and a specific experiment run with different interarrival times and threshold time see section 5.2).

The serial line system has been simulated with stochastic processing time in each machine, unreliable machines, fixed reliable buffer dimension and deterministic power consumption of the machine in the different energy states. The main parameters are summarized in Appendix B.

The power profile of the machines is the one already presented in the example Table 1. We note that we tested the system with a specific failure configuration along the serial line, that we called 'increasing MTBF' as described in Appendix B.

5.1 Validation of the simulation model

Our simulation model has been tested firstly with step-by-step simulation runs at slow speed in very basic scenarios and situations to check for proper behaviour of the system in each step. First simulation run were used to assess the simulation time needed to reach convergence of the results, by means of Welch procedure (Macchi and Terzi, 2009). We decided for a simulation run length of 100,000 cycles. Then we validated the model both with reliable and unreliable machines assumptions. In the latter case, we took as a reference previous published work (Vouros and Papadopoulous, 1998), specifically a system with the same configuration as in our experiments (4 machines and finite buffers), without energy saving policy, in order to compare the value of performance (throughput) of our simulation model in different buffer configurations. Appendix C shows the comparison in terms of throughput, which differs maximum for 0.3% from the reference taken.

5.2 Experiment and results

We recount in this paper the first run of experiments, that is part of a more complex design of experiments which included four controllable factors such as part interarrival time (IAT, 5 values), threshold time (TT, 4 values), idle power (2 values), MTBF (2 possible trend, increasing and decreasing from M1 to M4), for a total of 80 experiments.

We focus then on the experiments conducted with CJA policy by varying interarrival IAT with values MM:SS {00:30, 1:00, 1:30, 2:00, 2:30} and threshold time TT {00:25, 00:40, 1:00, 1:30}, see Appendix D, which shows the energy saving, in terms of difference with the baseline without energy saving policy, in the range of 4% to 36%, with a constant and null throughput variation with respect to baseline without energy saving policy.

The results of our experiment are graphically summarized in Figure 5, based on a bubble graph in which bubble size represents the percentage of energy saving while varying IAT and TT, given fixed value of Idle Power (4kW) and increasing MTBF values along the serial line.

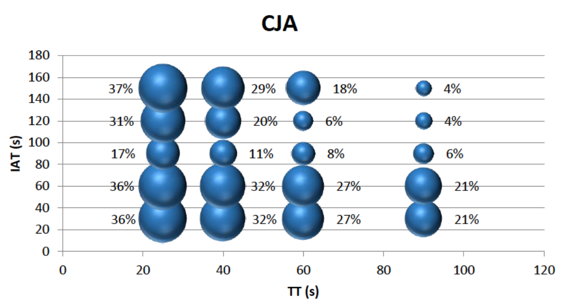

Figure 5: Energy saving varying IAT and TT, fixed idle power (4kW) and increasing MTBF configuration (cit.)

At first, we notice that, with threshold time TT increasing, the energy savings decrease: this is sensible, because there are less opportunities for the control policy to enable stand-by mode when the processing ends.

On the other hand, we notice, a somewhat unexpected effect in the energy saving quantity: for a given TT there is a specific value, a 'turning point' (TP) along the vertical axis, in which the saving bubbles reach a minimum size, different for each TT value and occuring for higher IAT with TT increasing. The presented experiment plan do not allow us to provide explanations of the measured behavior. It is obvious that the energy saving increases as the system saturation decreases, with IAT increasing. We need more experiments to explain why energy savings occur with low IAT, that is, with high system saturation, which contradicts what occurs in single machine systems (Prabhu et al. 2012).

6. Conclusions and further work

This article presents an effective energy saving control policy that can be enacted in each machine of a serial line, enabling decisions based on real-time information instead of statistically-based forecasts of part arrival rates as in the previous research. Additionally, with the proposed approach the energy aware serial line can be seen as a Level 5 5C Cyber Physical system, provided with autonomously self-configuration and self-optimization, that might be enabled by the presented BEinCPPS architecture. The research, to the best of the authors' knowledge, has a relevant importance for researchers in sustainable and energy and resource efficient production systems and practitioners, for the novel contribution on flow line and machine control, and for the approach that allows operationalization of the vision of Industry 4.0, by the proposed architecture already available to be tested in practice.

Future work will include experimentation of the CJA policy by means of a wider Design of Experiments plan, in order to improve the insights obtained so far. Furthermore, the study of the proposed energy saving policy can be extended to other production configurations, such as parallel machines, or, even job shop systems, with extension to other types of resources, beside energy.

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Appendix A.

Simtalk code for CJA policy, machine 1, activated when machine 1 ends processing.

```
is
-- local variables declaration
            i,j : integer;  t1, setup : time;
do
-- code CJA policy
            --Save the Simulation time
            t1 := EventController.SimTime;
            --Update Last_job1 to calculate the next exit times
including the setup time
            Last_job1 := @.name;

            --Get information on current (next) job
            f Buffer0.NumMU = 0 then
            for i := 1 to 4 loop
            Current_job1[i,1] := void;
            next;

            --if Buffer0 empty then machine1 stand-by
                        flag1 := "standby";
                        --make the beginning time of standby visible to
            calculate the entry time of the next current job
                        Standby_begin1 := t1;
            else
                        --if Buffer0 is not empty
                        flag1:= "operational";
                        --Get information on current (next) job
                        - Get name
                        Current_job1[1,1] := Object_buffer0[1,1];
                        --Get entry time
                        Current_job1[2,1] := t1;
                        --Get processing time + setup time
                        for i := 1 to Machine1_ProcTime.dim/2 loop
                                    if Machine1_ProcTime[1, i] =
                        Current_job1[1,1] then
                                    Current_job1[3,1] :=
                        Machine1_ProcTime[2, i];
                                    end;
                        next;
                        j:=SetupMatrix.getColumnNo(Current_job1[1,1]
            );
                        for i := 1 to Machine1_ProcTime.dim/2 + 1 loop
                                    if SetupMatrix[0,i]= Last_job1 then
                                    setup := SetupMatrix[j,i];
                                    end;
                        next;
                        Current_job1[3,1] := Current_job1[3,1] + setup;
                        --Get exit time
                        Current_job1[4,1] := Current_job1[2,1] +
            Current_job1[3,1];
            end;
            -- If the buffer is empty, put the machine in standby
            if flag1 = "standby" then
                        machine1.EnergyTargetState := "Standby" ;
                        Counter_rampdown1:=Counter_rampdown1 +
            1; -- to calculate the energetic consumption
                        else machine1.EnergyCurrentState :=
            "Operational";
            end;
end;
```

Appendix B.

Machine - system parameters (cit.)

Variable	Type	Value
Processing time	stochastic	Normal, Mean 1 min, std deviation 4 sec
Set up time	deterministic	0 sec
Mean Time Beetwen Failures (MTBF)	Stochastic (increasing MTBF along the line)	Neg-exponential, mean (M1: 20 min; M2: 50 min; M3: 100 min; M4 1000 min)
Mean Time Thru Repair (MTTR)	stochastic	Neg-exponential, mean 4 min
Power down t.	deterministic	10 sec
Ramp up t.	deterministic	variable
Buffer speed	deterministic	infinite

Appendix C.

Throughput validation, unreliable mach. model (cit.)

Buffer allocation (B1, B2,B3)	Throughput Previous work	(part/min) Our simulation model	Differenc e %
(1,1,1)	0.5916	0.59048	0.19%
(1,2,1)	0.6155	0.61400	0.24%
(2,2,1)	0.6378	0.63589	0.30%
(2,2,2)	0.6563	0.65591	0.06%
(2,3,2)	0.6725	0.67250	0.00%
(3,3,2)	0.6890	0.68857	0.06%
(3,4,2)	0.7007	0.70066	0.01%
(4,3,3)	0.7129	0.71218	0.10%

Appendix D.

Experiment 1, varying IAT and TT, fixed idle power (4kW) and increasing MTBF configuration, baseline: no energy control (cit.)

Threshold time TT (sec)	Inter Arrival Time IATM (MM:SS)	Throughput variation %	Energy saving %
25	00:30	0,000%	36%
25	01:00	0,000%	36%
25	01:30	0,000%	17%
25	02:00	0,000%	31%
25	02:30	0,000%	37%
40	00:30	0,000%	32%
40	01:00	0,000%	32%
40	01:30	0,000%	11%
40	02:00	0,000%	20%
40	02:30	0,000%	29%
60	00:30	0,000%	27%
60	01:00	0,000%	27%
60	01:30	0,000%	8%
60	02:00	0,000%	6%
60	02:30	0,000%	18%
90	00:30	0,000%	21%
90	01:00	0,000%	21%
90	01:30	0,000%	6%
90	02:00	0,000%	4%
90	02:30	0,000%	4%