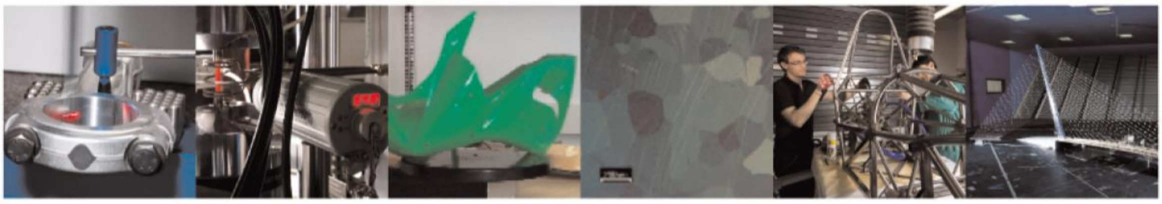

An energy consumption evaluation methodology for a manufacturing plant

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An energy consumption evaluation methodology for a manufacturing plant

A. Cataldo, R. Scattolini, T. Tolio

Abstract— **The energy efficiency of manufacturing systems is a topic of paramount interest, and reliable methods for modeling the energy consumption of machine tools are of fundamental importance for the design and management of production plants. For these reasons, this paper proposes a approach, named aCtuatorS Methodology (CSM), for modeling and predicting the energy behavior of discrete systems, i.e. systems where the energy consumption is mainly due to the on/off switching of the actuators governed by the control logic. CSM is then used to compute the energy consumption of the pallet transport line of a de-manufacturing pilot plant. A dynamic Discrete Event Simulator (DES) is first used to estimate the instantaneous overall energy consumption based on the absorbed power of each actuator and to complete a preliminary simulation study. The value of the energy consumption estimated with CSM is then compared to the real value measured on the transport line. The results achieved confirm the very good agreement between the behavior of the system predicted with CSM and the measured data.**

I. INTRODUCTION

Improving the energy efficiency of manufacturing production systems is nowadays a topic of paramount interest. In fact, the need to limit the CO_2 emissions [1], [2], resize the factory energy supply infrastructure, and minimize the energy consumption, represent factors that lead to equalize global living standards at the level of the industrialized regions [3] and to create new perspectives on energy efficiency in business decisions [4], [5], besides saving plant installation and production costs.

In order to design and manage energy efficient factories [6], [7], manufacturing companies require tools [8]-[11] for the prediction and computation of the energy consumption of process equipments (PE). Interesting reviews of the main approaches proposed so far can be found in [12], [13]. Many of these methods are based on Discrete Event Simulation (DES), see e.g. [14], [15]. In particular, the widely popular approach proposed in [14] introduces the concept of "Energy Block", i.e. the specific energy consumption behavior that a machine can assume in its operating states, like "turned-off", "start-up", "warm-up", "stand-by", "processing" or "stopping". By associating to each operating state an energy consumption pattern, identified by a power profile, it is possible to compute the overall energy consumption of the machines in different operating conditions. Further extensions of this approach have been reported in [15], [16], where the plant auxiliary systems have also been considered. In [17]-[19] the operating states of the process equipments and the associated energy consumption have been modeled in terms of Finite State Machines (FSM), see [20]-[22], a formalism suitable for dynamic simulation. A refined approach has been implemented in [23], where three different aspects of PE are taken into account, namely the mechanical, the logic control algorithms and the energy characteristics. While the mechanical behavior is modeled by means of DES, the logic control and energy aspects are described as FSM. In any case, it must be recalled that the accurate knowledge of many plant parameters, which can be directly measured, computed, or derived from technical nominal data, is fundamental for the proper computation of the energy consumption of the machines, see [24]-[26].

A drawback of the approaches based on the use of Energy Blocks can be due to their limited flexibility and scalability properties. In fact, the number of operating states, and the associated required power profiles, are in general variable and depend on the specific product to be processed in terms of the machining operations and production process technology, the material to be machined, the topology of the system, the adopted control logic. Therefore, when these conditions change, it can be difficult to compute, or reliably estimate, the energy consumption and the power peak loads. Notably, this information would be very useful both to the plant designers and to the management engineers: for the first ones to optimize the factory layout still during the plant design workflow phase, while for the second ones to optimize the on-line control of the production system according to specific performance indexes.

Motivated by the above reasons, this paper proposes a DES-based approach for the computation of the energy consumption of discrete systems, i.e. systems where the energy consumption is mainly due to the on/off switching of the actuators governed by the control logic. In the proposed method, named aCtuatorS Methodology (CSM), the modeling phase includes both the mechanical behavior of the system and the analysis of the actuators' characteristics, typically electric motors or pneumatic actuators, in terms of their absorbed power. In this way the resulting DES model is suitable to dynamically describe the energy consumption due to the logic state (on/off) of each actuator managed by the emulated plant control system. Then, based on the actuators' absorbed power parameters, specified in terms of either field measurements or nominal data, the instantaneous power required by each machine [27], [28] and by the whole production plant is computed. It follows that the evaluation of

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the energy behavior is largely independent of the factors defining the operating states of the machines and of the adopted control strategy, since it is based on the effective power instantaneously absorbed by the active actuators [29]. On the other hand, CSM does not consider many basic functions of a process equipment, like lubrication, chip removal, tool changing and so on, which can often dominate the energy requirements, see [30].

The potentialities of CSM have been tested on the pallet transport line of a real de-manufacturing pilot plant [32], [33], where the main energy consumption is due to the activation of the actuators moving the pallet from a transport module to an adjacent one. In order to implement and validate CSM in the considered test case, a Dynamic Control Platform for Industrial Plants (DCPIP), based on the C++ object oriented programming language, has been designed. Then, the pallet transport line has been modeled into the SIMIO DES platform [34] interfaced to the DCPIP. Finally, the DCPIP has been connected to the pilot plant itself and the measured power effectively absorbed by the system has been compared to the value computed in simulation. The results achieved show that CSM is able to provide an accurate prediction of the power absorbed by the transport line and of the overall energy consumption of the system.

The paper is organized as follows. The CSM basic concepts are described in Section II. Section III is devoted to describe its application to the transport line of the de-manufacturing plant. Specifically, the structure and behavior of the system are first described and the characterization of its actuators, in terms of absorbed power, is introduced. Then, the structure of the control system is discussed together with the DCPIP characteristics. In the Section IV finally, the simulation and experimental results obtained with CSM are presented and compared. Some conclusions are drawn in Section V, where also the future developments of this research activity are sketched.

II. THE CSM ENERGY CONSUMPTION METHODOLOGY

The basic idea of CSM consists of associating a specific power profile to each actuator driven by its logic control action and considered in the DES model of the process equipment. Specifically, CSM can be summarized as follows:

- Assume to have n actuators whose state (switched on/off) can be modified at fixed and synchronous time intervals Δt. Usually Δt also corresponds to the adopted simulation step time.
- Letting t be the continuous-time index, for each actuator define by $Act_i(t)$ the Boolean control variable corresponding to the activation/deactivation command, i.e. $Act_i(t)=1$ if the *i-th* actuator is working at time t while $Act_i(t)=0$ if the actuator is in idle.
- Denote by $PAct_i$ the (known) absorbed power of the *i-th* actuator in working conditions. For simplicity we consider here $PAct_i$ as constant, although this assumption could be easily relaxed to consider time varying power profiles or modulating control actions.
- Compute the instantaneous absorbed power of the *i-th* actuator at time t as

$$PT_i\,(t)=PAct_i \cdot Act_i(t) \tag{1}$$

and the total absorbed power as

$$PT(t)=\sum_{i=1}^{n} PT_i(t) \tag{2}$$

- Compute the total energy consumption at any time $t=k\Delta t+\tau$, $k=0,1,2,\ldots$, with τ belonging to the interval $[0,\Delta t)$, as

$$E(k\Delta t+\tau)=E(k\Delta t)+PT(k\Delta t)\tau \tag{3}$$

Concerning this procedure, some remarks are in order. First, from eq. (2) it is apparent that small size actuators can be neglected, with significant advantages in terms of modeling effort. However, some care must be placed in removing actuators which, although characterized by a small instantaneous absorbed power, remain active for long periods of time. In fact, their contribution to the total energy consumption could be significant, as apparent from the integral nature of eq. (3).

A second consideration concerns the power profile $PAct_i$. As already noted, and extensively discussed in [10], the machine absorbed power profile depends on many factors, such as the specific operating machine technology, the material to be machined and the product to be produced in terms of machining process. Therefore, it would be useful to design a software data structure able to set the most suitable instantaneous power value to be assigned to $PAct_i$ at each simulation step. In this regard, nominal data taken from the technical datasheets, or measured from the field, can be used, see [25].

In general, compared to the approaches requiring the definition of the energy states of the process equipment, CSM is simpler, since the description of the control behavior is often already available from the control engineers who design the control system. In addition, as clearly expressed by eqs. (1) and (2), the estimate of the maximum power peak is immediate. This implies that, in case of modified control sequences, there is no need to re-analyze the system from the point of view of new energy states, which in turn would require additional field measurements and the power profile reformulation. This is very important in the industrial production process design to guarantee flexibility to the plant designer and to the control engineers. Indeed, with CSM it is easy to design and simulate the process plant, and then to evaluate the total absorbed power maximum peak according to the defined plant control policy. In addition, it is possible to modify the plant layout and the control system functionalities in order to limit the plant power requirements, so obtaining significant savings in the production system costs both in terms of electrical power supply infrastructure and of energy purchasing [31].

III. THE APPLICATION OF CSM TO A DE-MANUFACTURING PLANT

The de-manufacturing pilot plant considered for the validation of the CSM approach, shown in Figure 1, is located in the laboratory of the Institute of Industrial Technology and Automation, National Research Council in Italy (ITIA-CNR). The plant is finalized to the re-manufacturing, re-use and recycling of products and components; specifically, it has been designed to test, repair, or destroy faulty electronic boards [32], [33].

Figure 1: The de-manufacturing pilot plant

General description of the system

A schematic representation of the de-manufacturing plant is reported in Figure 2. With reference to the symbols of this figure, the sequence of actions performed by the system are the following. First, the Load/Unload Board cell M_1 places the faulty board on a pallet, which is then loaded on a transport line made by fifteen transport modules TM_i ($i=1,\dots,15$). The transport line moves the pallet towards the Testing machine M_2 [35], where the electronic board is tested and its faulty component is identified. The pallet is then moved to the Reworking machine M_3 where the damaged electronic component is substituted. Finally, the electronic board is sent again to the Testing machine and, if it is properly working, it is moved back to the Load/Unload Board cell M_1 and stored. Otherwise, the board is sent to the Discharge Board machine M_4 to recover the raw material.

The transport modules TM_i are connected together to guarantee modularity and flexibility. On a transport module, up to three pallets can lay in adjacent positions, called *Buffer Zones* (*BZ*), and referred in the sequel as $BZ_{i,j}$ to denote the *j-th* position ($j=1,2,3$) of the *i-th* transport module.

Actuators

Four actuators are available in each transport module to move the pallet, namely, the Main Track motor (*M_Track_F/B*), the Stacker Crane Left/Right motor (*Sc1/2_L/R*), the Stacker Crane up and down pneumatic actuator (*Sc1/2_U/D*) and the block pallet piston (*Ev2A*), see Figure 3.

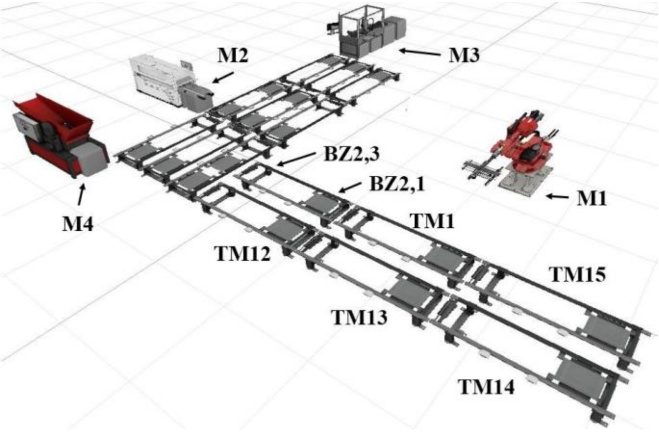

Figure 2: The de-manufacturing pilot plant structure

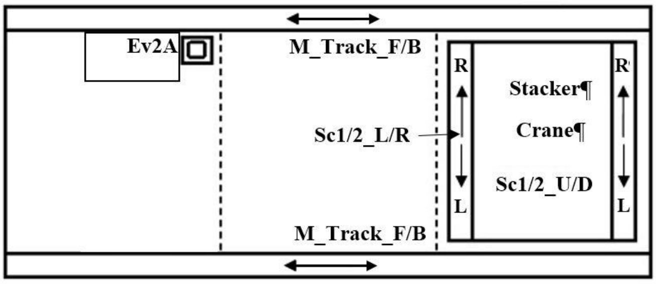

Figure 3: Actuators schema of the transport module

The nominal absorbed power of the actuators is reported in Table 1.

Table 1: Actuators' characteristics

Actuator	*nominal absorbed power*	*Equivalent electric energy*
M_Track_F/B	64W	
Sc1/2_L/R	64W	
Sc1/2_U/D	1.3W	1.9J
Ev2A	1.3W	0.8J

The data in Table I concerning the pneumatic actuators *Sc1/2_U/D* and *Ev2A* deserve some comments. First, it must be noted that for these elements, the energy required by the auxiliaries, i.e. the compressor, must be considered, see [15], [16], [36]. Specifically, the *Sc1/2_U/D* actuator remains in the Switched On state for about 1*s*, that represents the interval of time needed to complete the Stacker Crane up or down movement. This means that for each movement the *Sc1/2_U/D* energy consumption E_{EvSc} is

$$E_{EvSc}=1.3\cdot 1 =1.3\ J \tag{4}$$

Moreover, also the compressed air consumed by *Sc1/2_U/D* must be considered. According to [16]-[17] the required energy can be translated into equivalent electrical power as follows. The pneumatic cylinder that moves up and down the Stacker Crane has a diameter equal to 30 *mm* and a length equal to 10 *mm* which corresponds to a volume of air equal to 7 *ml* at the atmospheric pressure. From [29], the equivalent electric energy required by the compressor, used in the de-manufacturing plant, to compress 1 *Nl* of air to a pressure of 7 *bar* is 275 *J/l.* This means that the equivalent electric energy E_{Sc} required to move up the Stacker Crane is equal to

$$E_{Sc}=275\cdot 7\cdot 10^{-3}\cong 1.9\ J \qquad (5)$$

as reported in Table I.

In (4) the energy consumption is calculated as the product between electric power and time, while (5) represents an energy contribution independent of time. As it will be discussed below, this implies that the amount of energy calculated by (4) depends on the interval of time in which the actuator is switched on, while the second term depends only on the number of activation cycles of the actuator.

Finally, two additional considerations are in order. The first one concerns the amount of equivalent electric energy $E_{eq}Act_i$ in the period of time during which the actuator is switched on. Since the adopted pneumatic actuator consists of a single effect piston, so that the return movement is carried out by a spring, the equivalent energy contribution must be computed only once for each of the *mi* actuation cycle. The second consideration concerns the step that affects the total energy consumption function due to the equivalent electric energy consumption, which is is independent of the simulation interval of time Δt. These two considerations allow to extend (3) as follows:

$$E(k\Delta t+\tau)=E(k\Delta t)+PT(k\Delta t)\tau+$$
$$+\sum_{i=1}^{n}E_{eq}Act_i\cdot\left[\sum_{j=1}^{mi}pulse(Act_j(k\Delta t)\right] \qquad (6)$$

where the function $pulse(Act_j(k\Delta t))$ is *1* in the *j-th* period of time during which the *i-th* actuator is switched on, 0 otherwise.

Similar considerations hold true for the piston *Ev2A* used to block and unblock the pallet. The nominal electric power absorbed by the electro-valve that drives the piston requires 1.3 *W* for the same interval time of 1 *s* and then, as in (4), the consumed energy is equal to

$$E_{EvEv2A}=1.3\cdot 1=1.3\ J \qquad (7)$$

The pneumatic piston has a diameter equal to 20 *mm* which leads to

$$E_{EV2A}=275\cdot 3.14\cdot 10^{-3}\cong 0.8\ J \qquad (8)$$

Control system structure

More than one pallet can be placed on the transport line at the same time, and the goal of the control system is to determine, at any time instant, the movement of the pallets along the line to optimize the throughput of the system, to avoid deadlocks, to minimize the overall energy consumption and the absorbed power. In turn, this is equivalent to compute the commands to the actuators of the transport modules which allow for the pallets movements. With this objective in mind, the control system has been designed according to the hierarchical structure shown in Figure 4. At the higher level, an optimization algorithm recursively computes the optimal movement of the pallets along the transportation line, i.e. the control sequences to be actuated, based on the current status of the system given by the number of pallets on the conveyor and the status of the machines. A detailed description of the implemented high level control algorithm is reported in [35]. At the lower level, a set of Programmable Logic Controllers (PLC), one for each transport module, acquires the sensors' signals and drives the actuators to implement the required control actions. The two control loops run at different time scales, the high level works with 1 *s* cycle time, while the sampling time adopted at the low level is equal to 100 *ms*.

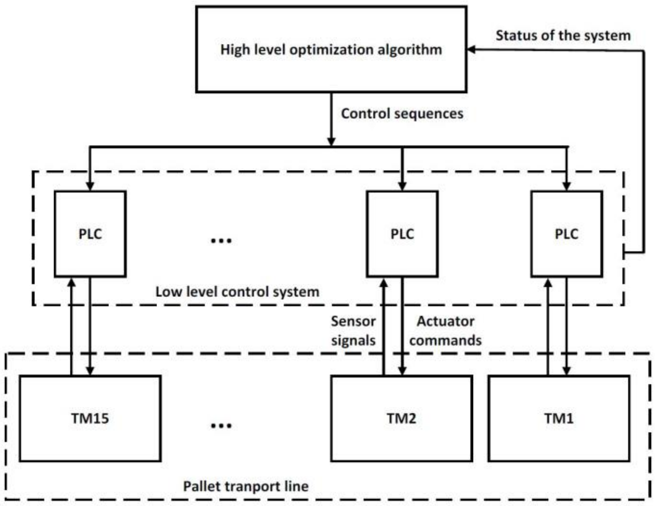

Figure 4: De-manufacturing pilot plant control architecture

Dynamic Control Platform for Industrial Plants (DCPIP)

A software platform based on the C++ object oriented programming language has been designed to implement the control scheme and to apply the CSM methodology. In an initial validation phase, this platform has been linked to a discrete event simulator of the plant. Then, it has been directly applied to the real transport line of the de-manufacturing system.

The platform is structured according to the following classes:

Task manager: manages the platform algorithm main cycle. The plant variables are acquired, the control algorithms are elaborated, and the control actions are sent to the plant, either the simulated or the real one;

Line supervisor: manages the data exchange between the plant and the control algorithms. Moreover it can stop running specific controllers or place them in the stand-by mode to emulate the off-line state of specific machines;

Machines: implements the data structure required by the control algorithms implementation;

Controllers: implements the high level control algorithms;

Interface: implements the data exchanging protocol between the plant and the DCPIP itself.

DCPIP first reads a file text containing the IDentification (ID) numbers of the machines of the system, controlled by the control algorithms. Based on this information, the constructors of the different software classes build the corresponding dynamic data structure and set the control and energy consumption algorithms.

DCPIP is also characterized by an interface for the data exchange that can be switched in a very easy way from one communication protocol to another one by simply setting the associated software class. This characteristic has been used for the CSM validation by firstly interfacing the DCPIP with the discrete event simulator of the transport line, and then by connecting it to the real plant. Notably, no modification of any DCPIP software data has been required.

Discrete Event Simulator (DES) of the plant

CSM has been first tested in simulation. To this end, the transport line has been modeled in the SIMIO DES platform according to the modeling and simulation techniques described in [23], that is by describing the control behavior of a machine by means of a FSM. The complete model has been obtained by aggregating fifteen transport module simulation models [37], each one based on the following main items: *(i)* a network of nodes and paths describing the flow of the pallet; *(ii)* a set of SIMIO processes used to manage the pallet movement thorough the network of nodes; *(iii)* the FSM control behavior, translated into C# code and implemented into SIMIO custom step in order to be integrated with the mechanical behavior; *(iv)* the computation of the total absorbed power and of the total energy according to (2) and (3). The choice to implement (2) and (3) into each transport module DES model depends on the specific control system architecture of the de-manufacturing pilot plant. In fact each transport module is managed by an own PLC which is deputed to drive the transport module working function by acquiring the sensor signals and by setting the actuator commands.

IV. SIMULATION AND EXPERIMENTS RESULTS

CSM applied to a simple introductory example

Consider the control sequence used to move a pallet from the buffer zone $BZ_{1,1}$ to $BZ_{1,3}$. Denote by P_Sc_D and P_M_Track the instantaneous power absorbed by the Stacker Crane down movement and the Main Track motor forward movement while Sc_D and M_Track_F the related Boolean control variables. For simplicity consider a constant power profile independent of time t. The transport module total absorbed power is

$$P_{TM1}(t)=P\_Sc\_D\cdot Sc\_D(t)+$$
$$+P\_M\_Track\cdot M\_Track\_F(t) \qquad (9)$$

Assume that the control sequence starts at time zero, see Figure 5. The Boolean control variables Sc_D and M_Track_F are set to one, and the total absorbed power is given by (9) in the whole interval time between the initial time and τ_2, when Sc_D(t) is set to zero, even if the power computation runs at each interval time Δt. This means that, if Δt is 100 *ms* and τ_2 is equal to 2 *s,* the absorbed power update (9) is run 20 times. At time τ_2 the power absorbed by P_Sc_D becomes null, and the TM_1 power computation value is only given by the second term in (9). At the instant time τ_5 the control action M_Track_F is also reset to zero, and also the second term of (9) becomes null.

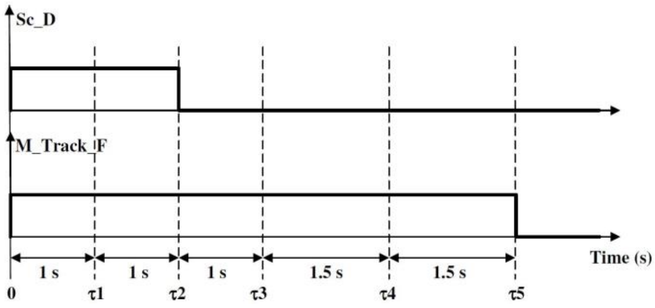

Figure 5: Control variables plot

The total absorbed power is plotted in Figure 6, where also the total energy consumption is depicted. In particular, in the first interval of time from zero to τ_2 the energy consumption is calculated as a straight line with gradient $tg(\alpha)$, equal to the total absorbed power value

$$dE_{TM1}/dt = P_{TM1}(t)=P\_Sc\_D+P\_M\_Track \qquad (10)$$

Then at τ_2 the total energy consumption is equal to

$$E_{TM1}(\tau_2) = 0+[P\_Sc\_D+P\_M\_Track]\cdot\tau_2 \qquad (11)$$

At this instant, the control action related to the Stacker Crane becomes null and only the Main Track power profile is integrated. In this way the gradient $tg(\beta)$ of the energy consumption curve decreases to the value

$$dE_{TM1}/dt = P_{TM1}(t)=P\_M\_Track \qquad (12)$$

At τ_5 the total energy consumption will be equal to

$$E_{TM1}(\tau_5) = E_{TM1}(\tau_2)+[P\_M\_Track]\cdot(\tau_5-\tau_2) \qquad (13)$$

which rearranged becomes

$$E_{TM1}(\tau_5) = (P\_Sc\_D\cdot\tau_2)+(P\_M\_Track\cdot\tau_5) \qquad (14)$$

Equation (14) shows that the total energy consumption is computed as the summation of the energy consumed by each actuator in all the intervals time in which they have been Switched On. After the time τ_5 the total energy consumption curve remains constant because the two actuators are Switched Off and then no power is absorbed.

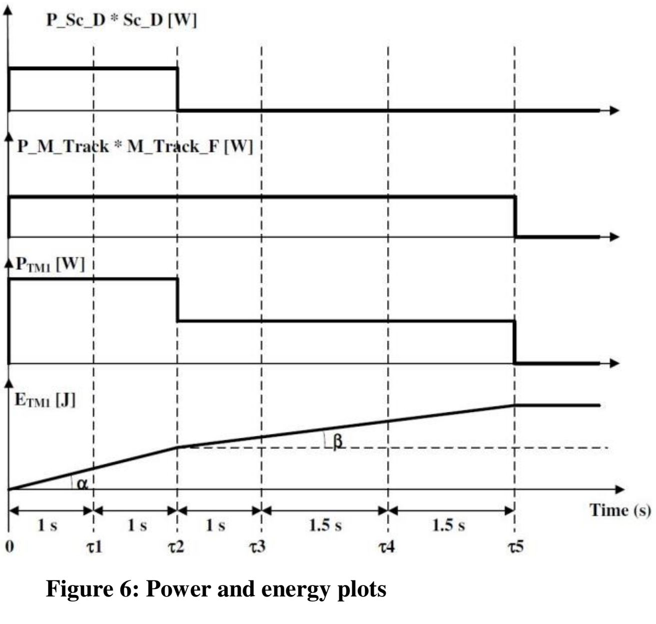

Figure 6: Power and energy plots

CSM applied to the simulated model of the pallet transport line

The constant power absorbed by the electronic devices of each transport module is equal to 30 W , for a total amount of 450 W. Based on the data reported in Table I and in view of the previous considerations, see (4)-(8), the contributions of the electro-valves to the overall absorbed power and energy consumption is negligible. Therefore, only the Main Track and Stacker Crane L/R power contributions have been considered in (1), while the contribution of the actuators Sc1/2_U/D and Ev2A has been neglected.

The simulation experiment consists of moving two pallets on the transport line according to the control sequence described in Table 2. Note that at most two actuators are activated at the same time to allow for a simple representation and analysis of the system's behavior. This control sequences have been implemented and run inside the DCPIP. In the simulation experiment, the DCPIP has been connected to the transport line DES model and the contribution of each transport module has been computed.

The total power profile and the consumed energy are shown in Figure 7 and Figure 8, respectively. It is apparent from Figure 7 that the constant power (450W) absorbed by the whole pallet transport line due to the electronic control devices, represents roughly the 70% of the maximum peak of absorbed power, which leads to the linear trend of the consumed energy shown in Figure 8. This is due to the small number of actuators switched on at the same time. The total energy consumption at the end of the simulation (102.9 *s*) is equal to 54558 *J*.

Table 2: Control sequence and actuators activation

Control step	***Step time***[a]	***Switched on actuator***	***Transport module***
1	0	*M_Track_F*	TM_1
		M_Track_F	TM_2
2	11.7	*M_Track_F* *M_Track_F*	TM_1 TM_2
		M_Track_F *Sc1_L*	TM_2 TM_3
3	20.9	*M_Track_F*	TM_2
		M_Track_F	TM_3
4	33.6	*M_Track_F* *M_Track_F*	TM_3 TM_4
5	40.0	*M_Track_F* *M_Track_F*	TM_4 TM_5
6	57.4	*M_Track_F* *Sc1_L*	TM_2 TM_3
		M_Track_F	TM_5
7	66.7	*M_Track_F*	TM_3
		Sc1_L *Sc1_R*	TM_5 TM_6
8	77.5	*M_Track_F* *M_Track_F*	TM_3 TM_4
		M_Track_F	TM_6
9	90.6	*Sc1_L* *Sc1_R*	TM_4 TM_8
10	98.9	*M_Track_F* *M_Track_F*	TM_6 TM_8

a. Step time (s)

In order to analyze more in detail the simulation results, consider for example the control step 1. The high level controller requires to move the pallet from $BZ_{1,1}$ to $BZ_{1,3}$ with the actuator *M_Track_F* of the transport module TM_1 , while the second control action moves the pallet from $BZ_{2,1}$ to $BZ_{2,3}$ with the actuator *M_Track_F* of TM_2. From the power profiles of these transport modules, reported in Figure 9 and Figure 11, it is possible to see that the total absorbed power rises from 30 *W*, i.e. their base power, to 94 *W*, and this value is maintained in the interval of time required to complete the pallet movement. Then, the power absorbed by each transport module falls down to 30 *W*. Correspondingly, as shown in Figure 7, close to the time instant 9 *s* the total power has a negative step equal to 64 *W*. This depends on the fact that, once the pallet has left the transport module TM_1, the corresponding actuator *M_Track_F* is switched off, while the actuator *M_Track_F* of TM_2 is still switched on. In fact, the analysis of the simulation results shows that *M_Track_F* of TM_1 switches off at time 9.1 *s* while *M_Track_F* of TM_2 switches off at time 9.6 *s*, when the total power absorbed by the transport line is brought back to the minimum value 450 *W*. In order to complete the analysis, the energy consumption of the transport modules TM_1 and TM_2 is shown in Figure 10 and Figure 12, respectively. From these figures it is easy to see that the energy consumed by the transport modules electronic devices, labelled Base, is greater than the total energy consumed by each actuator used to perform the pallet movement. This is due to the specific simulation experiment in which only two pallets have been moved, so that the contribution of the active actuators is quite small compared to the one of the Base energy consumption.

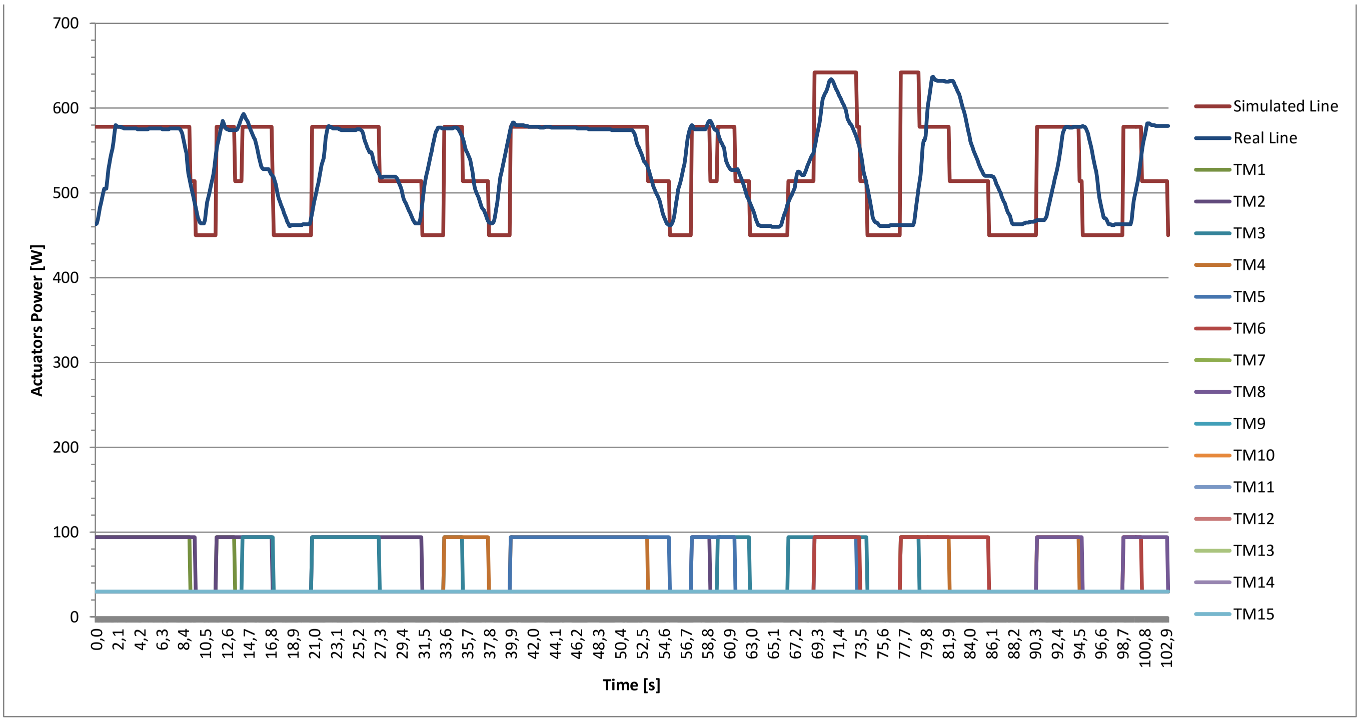

Figure 7: Pallet transport line power simulation and measurement results

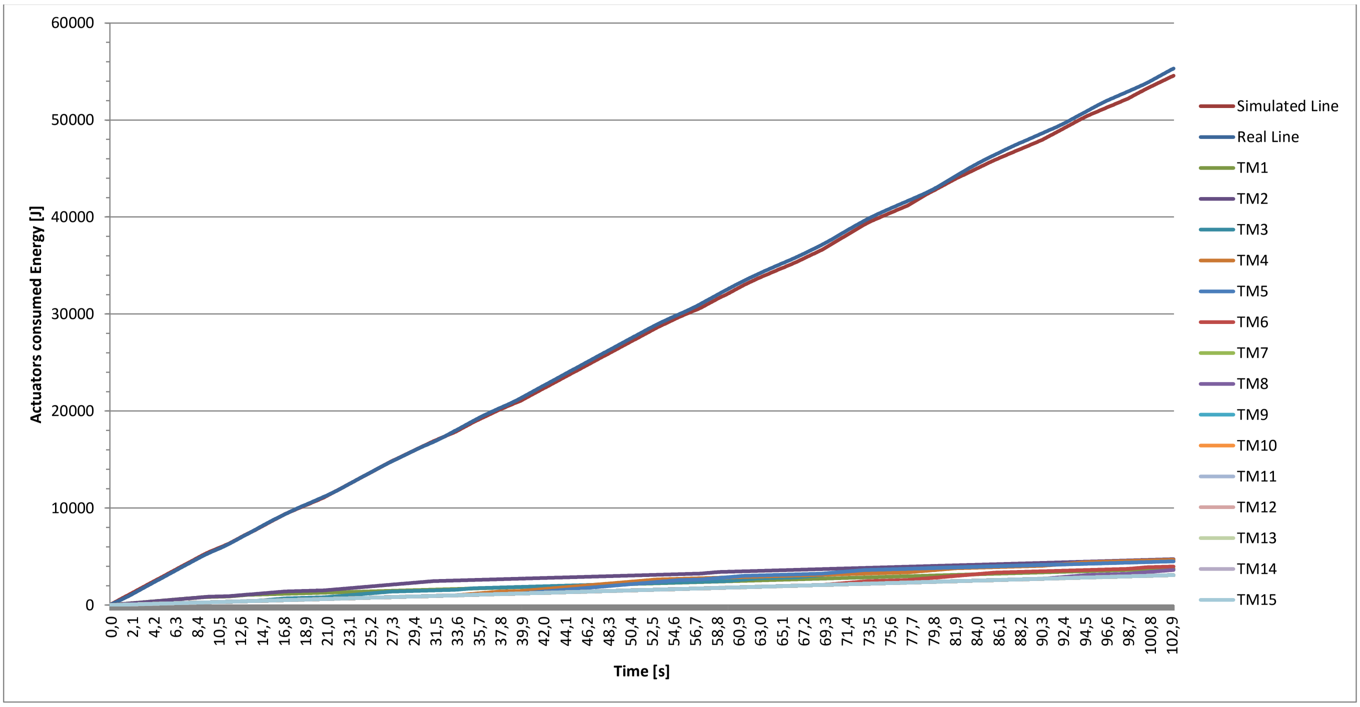

Figure 8: Pallet transport line energy consumption simulation and measurement results

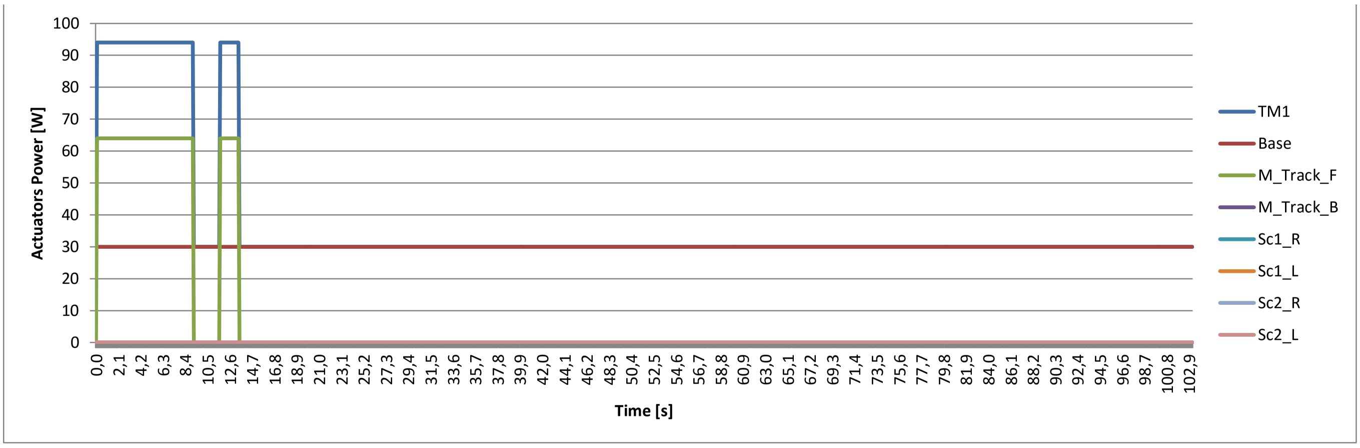

Figure 9: Transport module TM1 power simulation results

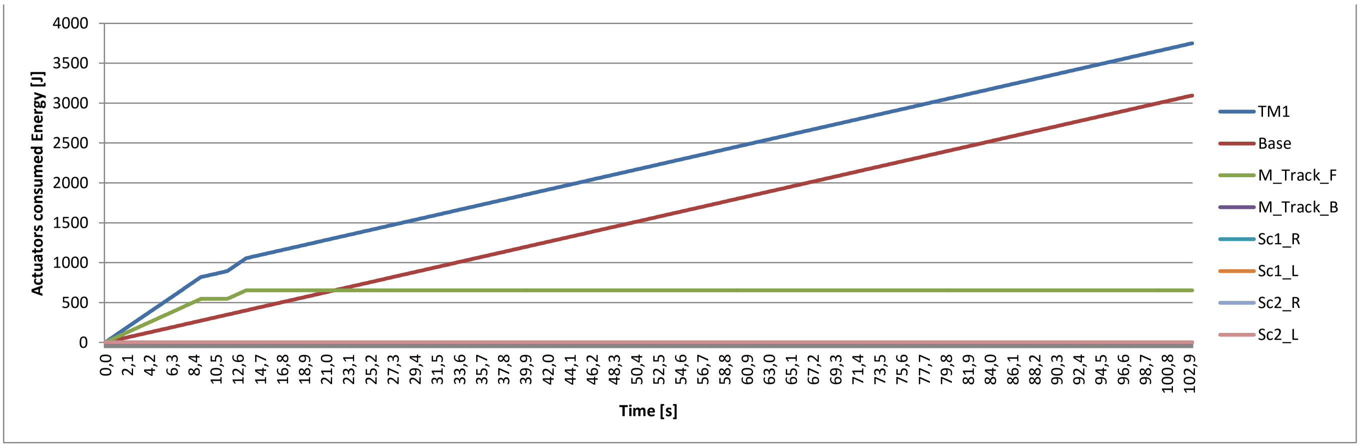

Figure 10: Transport module TM1 energy consumption simulation results

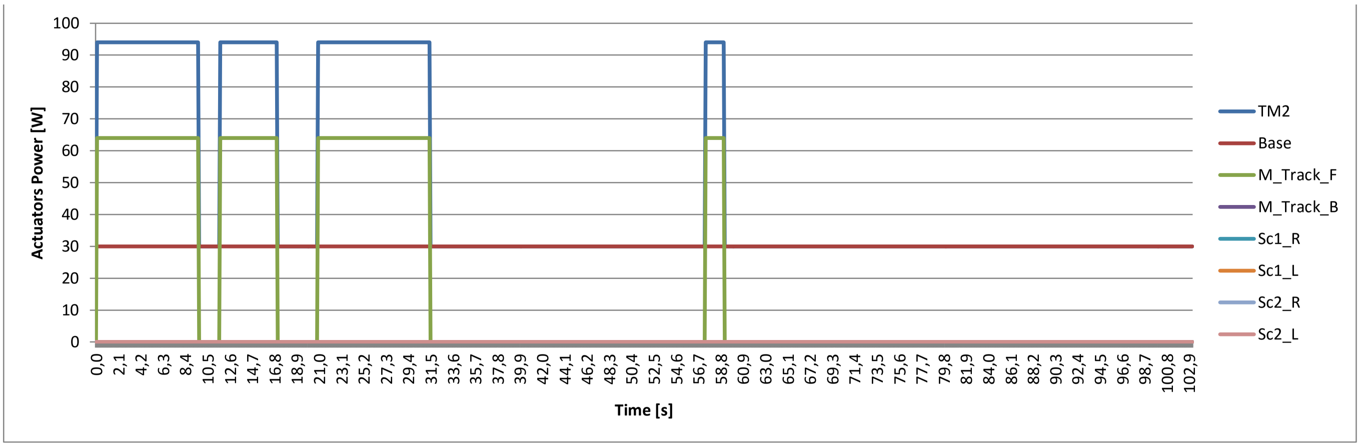

Figure 11: Transport module TM2 power simulation results

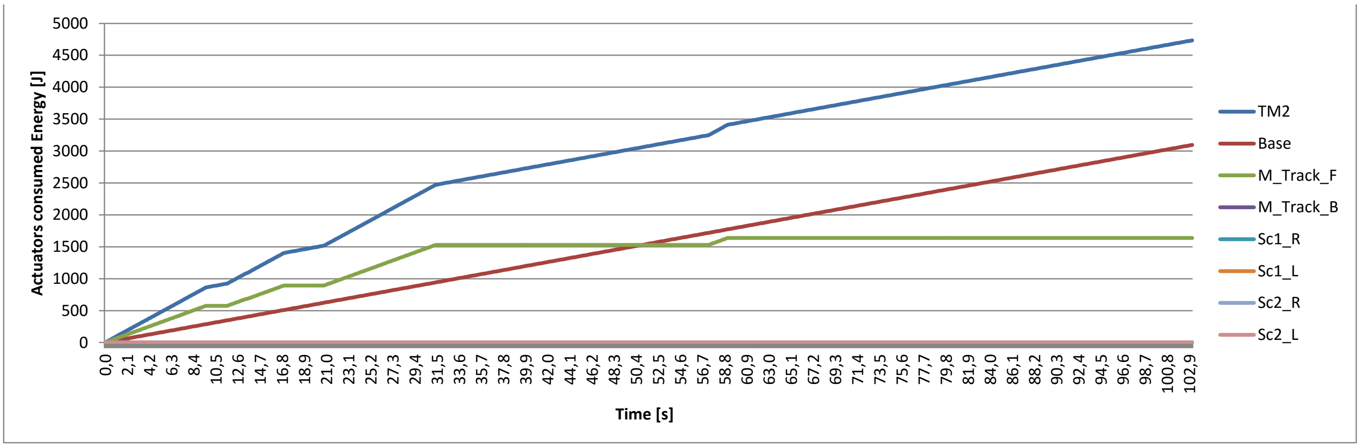

Figure 12: Transport module TM_2 energy consumption simulation results

CSM applied to the de-manufacturing plant

The Dynamic Control Platform DCPIP has also been used to control the real plant. In this case, the high level optimizing controller runs in DCPIP, while the low level controllers are implemented in the ISaGraf platform [38] by resorting to the IEC 61131-3 standard. The measurement instrumentation has been used to collect and store the power and energy consumption of the whole pallet transport line, see Figure 13.

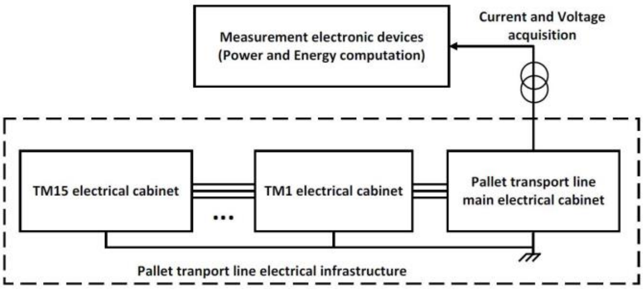

Figure 13: Measurement system architecture

The same control sequence considered in the simulation experiment and listed in Table 2 has been used. Since the available instrumentation is able to acquire only one measure of power and energy consumption, only their total value, referred to the whole transportation line, has been acquired. The measured transients are compared to those computed in simulation with CSM in Figure 7 and Figure 8, respectively.

From Figure 7 it is apparent that the transients of the absorbed power, due to the activation/deactivation of the actuators, are not pure steps, but exhibit a sort of "ramp-type" behavior. This is due to a filtering action performed by the measurement system. However, the effect of this filtering is negligible on the average, since the overestimated energy due to the actuators' switch on phase is compensated by the underestimated energy due to their switch off. As for the power peaks and their duration, Figure 7 shows a very good fitting between the simulated results and the field measurements.

Finally, Figure 8 shows that also the energy consumption computed with CSM and the simulation model fits well the real plant data. In fact, the difference between the measured and computed energy consumption at the end of the experiment is equal to 1589 J over real total consumption of 57522 J. In terms of power, the difference between the mean simulated and measured values is equal to 15 W, i.e. the 0.5% of the measured total absorbed power. This small difference is mainly due to the neglected effect of the actuators *Sc1/2_U/D* and *Ev2A*.

V. CONCLUSIONS

In this paper a new method, named CSM, is proposed for the simulation and prediction of the power peaks and the energy consumption of manufacturing systems where the energy consumption is mainly due to the on/off switching of the actuators governed by the logic control. CSM has been applied to compute the energy consumption and the power peaks of the transport line of a de-manufacturing plant made by fifteen transport modules and four working machines. The performance of CSM have been tested on the real system with satisfactory results.

Although CSM has been developed for a specific plant, it is believed that it can be of interest also in the analysis and design of other manufacturing systems. In fact, with CSM it is possible to compute the plant power and energy consumption during the production system design phase. This allows to design the control strategies focusing on the minimization of the energy consumption and the absorbed power peaks. In this way, the value of the peaks can be maintained under given thresholds with limited plant energy costs [31], and the plant power supply system can be appropriately sized.

Future developments will concern the testing of CSM in different and meaningful test cases. In addition, the characteristics of CSM will be generalized to allow it application to wider classes of manufacturing systems. To this end, a standardized simulation library of process equipments will be developed to support the engineers involved in the plant design activities.

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