Digital Manufacturing Tools Applied to Energy Analysis and Decision in Manufacturing Systems

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Abstract--**Global warming, outside pressures to the application of sustainable practices and rising energy prices are factors increasingly present in today's society. In addition, the cost of energy becomes increasingly significant, being an important vector to be considered in business competitiveness. Thus, this work includes the energy efficiency variables within the context of manufacturing systems analysis. The methodology includes the development of a simulation model over a digital manufacturing system, an emerging technology that seeks to improve the industrial plants' development processes by introducing new integrated software suites. The evaluated scenarios involve the collection and analysis of energy and manufacturing data of an automotive engine production line, where different simulation strategies were implemented aiming the overall electricity consumption reduction. The results show that the simulation of control actions through digital manufacturing systems allows not only getting a current situation diagnosis of the facilities, but also enables a more efficient use of available resources by identifying opportunities to increase energy efficiency indicators, even in well designed production systems.**

I. INTRODUCTION

Global climate changes, pressure to apply sustainable practices, generation costs, and transmission and distribution of electric energy consumption with growth perspective are factors which are increasingly being discussed by the society [4].

As electric energy is a primary element in the production of goods for the society, the costs involved and environmental impacts associated with its consumption are also progressively more influent in the manufacturers' operations [1].

Given this challenging, competitive, and regulated scenario, several studies confirm a significant potential to improve the energy efficiency indicators in the manufacturing industry, with a possibility of increasing 30% only by applying the current technologies [10]. However, correlating the use of technology with the operations executed in manufacturing systems represents a challenge due to the complexity of the production systems and the huge number of data sources [21]. In this case, statistical calculations, artificial neural networks, fuzzy logic, and systems simulation are four alternative approaches that may be applied to analyze the consumption of industrial installations, as simulation has proved to be a significant approach for this type of application [10].

The application of computational simulation systems proves to be a potential tool to analyze and support decision-making when facing the global energy efficiency of industrial installations. This happens because decisions have an impact on the energy consumption of a production system, and they are part of all the operation in an industrial unit.

In this context, the proposed study covers the generation of different simulation scenarios for a production line of automotive engine blocks, thus including the variables associated with energy efficiency within the context of analysis of manufacturing systems. The proposed analysis recommends reducing the global energy consumption of the line, considering the current relation of this variable with productivity, manufacturing processes, and the production programming of the industrial plant.

II. THEORETICAL REVIEW

A. Energy Management in Manufacturing

The manufacturing industry plays an indispensable role in the global economy and is responsible not only for transforming materials and information on goods for the satisfaction of human needs and other industries around the world, but also provide a significant portion of employment and represent great economic power. In contrast [16], the manufacturing sector also corresponds for 37% of total world primary energy consumption [11], which puts the costs involved and the environmental impacts as increasingly influential factors in the operation of these organizations.

Considering that manufacturing companies need energy as a primary element in order to produce goods for the society, limiting production is not a viable option. In this context, facing a scenario increasingly challenging, competitive and regulated, [10] argue that improving energy efficiency becomes an extremely promising option for manufacturing companies. In a complementary way, according to [22] to improve energy efficiency in manufacturing activities is an inevitable trend for energy conservation, emissions reduction and adherence to sustainability practices.

Considering the previous discussion, the energy efficiency theme has witnessed increase in its scope, going beyond the traditional energy-intensive industries such as steel, cement, chemical and pulp and paper. In [14] as noted by [6], in the sectors focused on discrete manufacturing, the attention of academic and industrial research for energy efficiency theme became visible from the 2000's, driven by tangible improvements in economic and environmental terms.

Despite the great efforts already undertaken, such as the isolated replacement of electric drives or integral improvements in production processes, there is still significant potential in the implementation of energy efficiency measures economically feasible for the manufacturing industry [2]. As presented in [1], new approaches must be developed which enable the implementation of energy efficiency solutions in dynamic manufacturing systems, which have demand conditions and changing requirements.

In this regard, the modeling processes of energy consumption can provide a better understanding of where and how power is being used, then allowing the identification of potential areas of improvement [20]. However, a thorough analysis of a production system should consider all the dynamics of the variables that make it up, adding to this assessment technical and economic aspects, such as the output of products, availability and costs involved.

B. Simulation Applied to Energy Efficiency

The discrete event simulation is often used in the design phase to evaluate concepts and improve system solutions before investment decisions are made. The common goal is to identify problem areas and to quantify and improve the performance of the production system, such as performance under average and peak loads, use of resources, workers and machines, personal needs, work shifts, bottlenecks and storage requirements of materials [9].

In this context, [20] indicate that the use of simulation of manufacturing systems is a promising way for addressing the new issues related to the environment, such as energy consumption, given the considered simultaneously with other traditional dimensions of analysis, such as cost, time and quality. The authors further state that the use of theoretical models for establishing an energy baseline is useful in identifying power optimization opportunities.

Initial studies using these tools for energy efficiency analysis in industrial plants were conducted by [17] and [18], which presented simulation models for analysis and reduction of energy consumption with a focus on smelters and their specific characteristics.

In addition to this initiative, [8] propose a simulation model that aims to reduce the energy consumption of a machine for the automotive industry during the design phases. Through simulation proposed by the authors it could be can identified the components with high power consumption while the machine is in idle state, thereby providing a design change on the machine automation system which resulted in a reduction of 3.2% of total energy consumption.

Study conducted by [12] also presents a simulation model of a production line, matching flow of materials and energy variables, resulting in the prediction of individual energy consumption per product variant produced as well as their trailers costs.

In addition to reducing consumption, recent academic studies have focused also on the use of simulation tools to explore reducing the electrical demand of manufacturing systems at peak times.

In [7], [19] and [3] are presented buffers application models aimed only at reducing the electricity demand during peak hours in multi-machine systems through the construction of intermediate stocks among the machines and changes in production planning for the off-peak periods.

However, in addition to production systems addressed by these tools and previous studies, the layout of plants, the dynamic behavior of the equipment as well as the design and the different stages of manufacturing a productive resource can take over its operation, among other factors, may have a major impact on energy consumption in the manufacturing units. Thus, the application of integrated digital manufacturing tools allows for more efficient and comprehensive analysis of industrial plants, adding new parameters to be treated simultaneously.

Moreover, as placed by [13] simulation tools can also be used in a broad yet largely unexplored field in order to study the energy behavior of productive resources across the different scenarios, allowing to obtain energy consumption forecasts and providing relevant information to the process decision-making, such as choosing the best supply contract and ideals shifts to the operation of a plant. These scenarios may involve the effects achieved through the application of different instruments, such as the relationship between energy states and the states of manufacture of machinery, inventory management and buffers and production planning [13].

In a complementary way, the authors also report that simulation environments, when properly supported by performance indicators allow not only the evaluation of different scenarios, but also the monitoring of the effectiveness of the improvement actions taken over time.

III. METHODOLOGY

In this work, production systems simulation models were created, with the allocation of additional data and power logic in order to obtain an accurate match to the system behavior and enabling the analysis of the results. The following activities were carried out:

a) acquisition of data related to energy performance of equipment and subsystems;
b) development and validation of models to obtain indicators;
c) representation and analysis of results.

The computer simulation software Siemens Plant Simulation® was used as a tool to analyze production systems and their energy systems in this work. As explained by [15], the simulators offer advantages such as relatively lower time requirement for building the model and ease of use supported by menus and friendly graphics.

The choice of a digital manufacturing system due to the focus applied in this research, which is directed to energy efficiency considering the relationship of this variable with productivity, manufacturing processes, production scheduling and interaction between environments that are an industrial plant.

This study is structured as follows: Section III presents the study procedures and the description of the covered system, encompassing the parameters considered and the proposed scenarios of evaluation used to support the validity of the results. Section IV presents the simulation studies carried out for evaluation of energy efficiency indicators in industrial installations, in addition to present and discuss the results achieved through the application of different strategies proposed. Finally, Section V summarizes the findings of the study, involving the contributions made and constraints encountered.

IV. SYSTEM DESCRIPTION

This work presents, through the application of simulation technique, a method of integration between the manufacturing states and the power management of multi-machine production lines.

Thus, it was selected as the basis for this study a production line responsible for the manufacture of engine blocks in an automobile industry [5]. This line consists of eighteen automated workstations and four buffers, each with storage capacity for 100 pieces. A simplified representation of this line and the respective flows are shown in Fig. 1.

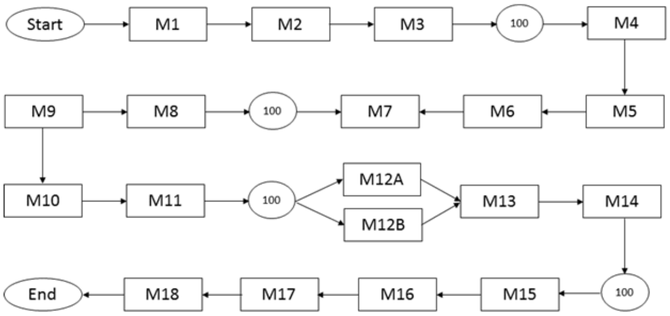

Fig. 1 – Engine production line

The production parameters of this engines line were extracted from the study presented by [5] and are shown in Table 1.

TABLE 1 – PRODUCTION PARAMETERS. ADAPTED FROM [5].

Station	Cicle Time (s)
M1	29.35
M2	24.43
M3	29.27
M4	28.94
M5	28.11
M6	28.99
M7	28.61
M8	28.4
M9	29.98
M10	28.37
M11	26.78
M12A	57.8
M12B	58.5
M13	30
M14	27.25
M15	30.81
M16	27.85
M17	28.98
M18	28

The choice of a line approximately synchronized operation decays about the importance of seeking opportunities to improve energy efficiency, even in production systems have well-designed originally.

For the correct establishment of relations between the manufacturing states and the line power management in the study were also identified possible energy states to be assumed by the equipment. Fig. 2 shows the diagram of the power states of the machines associated with the respective transitions and time.

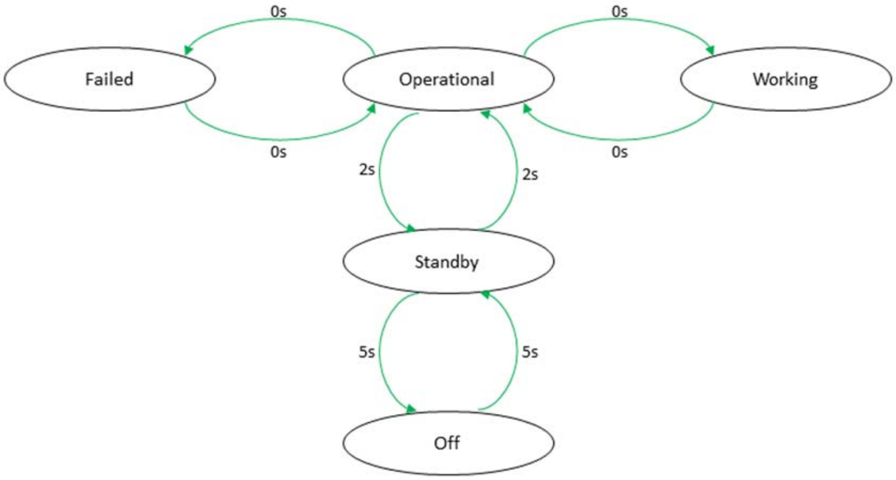

Fig. 2 – Energy State Diagram

TABLE 2 – ENERGY STATES. ADAPTED FROM [13].

Energy State	Description
Off	Equipment is off: no energy consumption
Standby	Equipment presents the most components off and is not ready to process parts. Only a few active components are maintained on and consume energy in order to reduce the time of reactivation of equipment.
Failed	Equipment is in maintenance, with some actions that require energy.
Operational	Equipment is not processing parts, but remains energized all the necessary components to resume production immediately upon request.
Working	Equipment is processing parts.

TABLE 3 – ENERGY PARAMETERS FOR THE EQUIPMENT OF THE LINE

Station	Working (kW)	Operational (kW)	Failed (kW)	Standby (kW)
M1	14.0	8.4	3.5	1.4
M2	24.0	14.4	6.0	2.4
M3	14.0	8.4	3.5	1.4
M4	15.0	9.0	3.75	1.5
M5	25.0	15.0	6.25	2.5
M6	25.0	15.0	6.25	2.5
M7	13.0	7.8	3.25	1.3
M8	15.0	9.0	3.75	1.5
M9	12.0	7.2	3.0	1.2
M10	14.0	8.4	3.5	1.4
M11	21.0	12.6	5.25	2.1
M12A	24.0	14.4	6.0	2.4
M12B	24.0	14.4	6.0	2.4
M13	14.0	8.4	3.5	1.4
M14	20.0	12.0	5.0	2.0
M15	12.0	7.2	3.0	1.2
M16	14.0	8.4	3.5	1.4
M17	14.0	8.4	3.5	1.4
M18	15.0	9.0	3.75	1.5

Each power state has an associated nominal power, which will be used to obtain the projections of consumption and electric power demand in the various proposed simulation scenarios. The description of the energy states that will be used for the production line analysis is presented in Table 2.

Through these data and machine information powers established by [7], [19] and [3], the values for each power state of the equipment making up the line have been made, as shown in Table 3.

For all equipment, the rated power considered for the off state is 0 kW.

It was adopted in this simulation producing a single engine block model. The energy states of the devices described above were parameterized through internal settings to the model, as well as their respective power ratings. Additionally, the following assumptions were adopted in the preparation of the model:

a) each station has a nominally constant speed, determined by the respective cycle time. A station can operate outside their nominal cycle in the absence of parts or locking of the following equipment;
b) there is a mechanism upstream of the line, which controls the continuous release of parts. Each piece is sent for processing on the first machine only if it is available to process it;
c) after completion of all processing, the part gets out of line and is forwarded directly to another plant section;
d) there is no rework or reject parts. All parts that complete the processing are considered good;
e) each equipment can assume the following power states: off, standby, failed, operational and working. The transition between two states is triggered by the occurrence of a control event such as arrival of a part or the absence of feedstock;
f) the production baseline for the system in question is 918 pieces as calculated in (1) for a period of 08 hours, considering it an ideal operating system, i.e., without external interference that may affect the overall performance of the line, such as the occurrence of failures and unplanned maintenance.

$$N^{\underline{o}}\,parts = \frac{Total\ Time - Heating\ Time}{Biggest\ Cycle\ Time} \rightarrow \frac{480\,\text{min} - 8{,}553\,min}{0{,}5135\,min} \rightarrow$$

$$N^{\underline{o}}\,parts = 918 \qquad (1)$$

The manufacturing plant operation was fixed at 03 shifts from 08 hours 07 days a week. For the study, the analysis and comparison of energy will be carried out through a shift of 08 hours. This period includes 8.553 minutes corresponding to the line heating, defined by the time required to fill the total system after the initialization of the empty line.

Setup operations are not considered in this study, as well as their energy states associated. The occurrence of failures and maintenance stoppages are also not included in this model.

On the comparative analysis of the context between different strategies proposed by this study, the following scenarios are proposed:

a) Scenario 1 - production line without unplanned stopping instances of equipment and assuming only the energy states "operational" and "working". This scenario aims to analyze the energy indicators in a situation without random disturbances and synchronized operation. The fact of considering only two energy states is related to the usual industry practice, placed by [5], in which many systems still operate in the absence of multiple operating states;

b) Scenario 2 - addition of the standby state to the stage 1. This scenario aims to assess the energy efficiency increase potential through the application of multiple operating modes with automatic transition in a situation without random disturbances and synchronized operation. The automatic transition between energy states will be implemented through content balancing strategy of the line buffers;

c) Scenario 3 - startup of the equipment in standby mode for scenario 2). This scenario aims to evaluate the impact on energy efficiency indicators of the line, considering the equipment of operation starting in standby mode and keeping the content of the buffer management routines presented in scenario 2.

V. RESULTS AND DISCUSSION

The results obtained through the study of an operating shift encompass both manufacturing parameters and variables related to energy consumption. Table 4 summarizes the main manufacturing data for the scenarios under consideration.

Considering a shift 08 hours of production, scenario 3 proposed produced 917 finished pieces, i.e. the implemented strategy resulted in the loss of a unit produced by shift in relation to scenarios 1 and 2, which represents a decrease of 0.109 % of total production. This loss is due basically to the sum of the transition time of the equipment from standby to operating / processing for the arrival of the first piece to be processed. This also impacts the amount produced by equipment, represented by slight individual production variation observed when compared to previous scenarios.

Regarding the number of parts in process resulting in the shift finishing time in the allocated buffers, and machines, Table 5 presents a comparison between the evaluated scenarios:

TABLE 4 – PRODUCTION DATA

Station	**Quantity Produced (un.)**			**Processing Time (%)**		
	Scenario 3	**Scenario 2**	**Scenario 1**	**Scenario 3**	**Scenario 2**	**Scenario 1**
M1	940	944	981	95,80	96,29	100,00
M2	940	943	980	79,74	80,08	83,16
M3	940	942	979	95,53	95,84	99,54
M4	932	937	978	93,66	94,16	98,32
M5	931	937	977	90,87	91,46	95,40
M6	931	937	976	93,71	94,32	98,29
M7	931	937	975	92,49	93,08	96,91
M8	928	928	954	91,52	91,61	94,09
M9	927	927	953	96,51	96,60	99,21
M10	926	927	952	91,23	91,32	93,79
M11	925	927	951	86,03	86,20	88,45
M12A	462	462	474	92,74	92,83	95,30
M12B	461	462	474	93,77	93,85	96,35
M13	922	923	947	96,06	96,15	98,72
M14	921	922	946	87,17	87,24	89,58
M15	919	920	920	98,42	98,52	98,52
M16	919	920	920	88,87	88,97	88,97
M17	918	919	919	92,38	92,48	92,48
M18	917	918	918	89,16	89,26	89,26

TABLE 5 – FINAL BUFFERS AND MACHINES ALLOCATION

Station	Processing Parts (un.)		
	Scenario 3	Scenario 2	Scenario 1
Buffer 1	7	5	0
Buffer 2	2	8	20
Buffer 3	0	1	1
Buffer 4	1	1	25
Machines (global)	13	12	18
TOTAL	**23**	**27**	**64**

It is observed that the largest allocation parts in process occur in scenario 1. The results observed for the scenarios 2 and 3, with lower occupancy of the buffers, arises from the content of balancing routines of buffers implemented to reduce energy consumption in these scenarios as shown in Fig. 3.

In a second approach, the simulation also provides the data for the energy behavior of the line during the period considered. Tables 6 and 7 show the absolute values of individual consumption in the different states of each equipment and the overall line consumption, as well as a comparison among the scenarios.

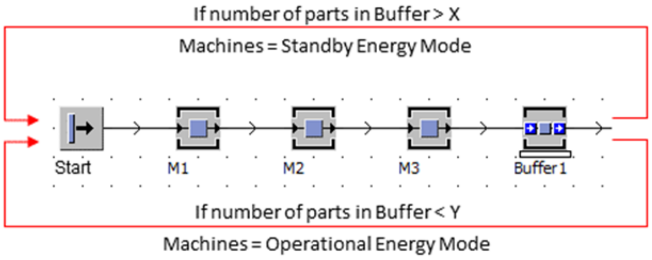

Fig. 3 – Buffers content balancing strategy

TABLE 6 – ENEGY DATA (1)

Station	Total Consumption (kWh)			Consumption - working (kWh)		
	Scenario 3	Scenario 2	Scenario 1	Scenario 3	Scenario 2	Scenario 1
M1	107.82	108.31	112.00	107.29	107.84	112.00
M2	172.35	173.08	179.06	153.09	153.74	159.66
M3	107.65	108.06	111.79	106.99	107.34	111.48
M4	113.58	114.29	119.19	112.39	112.99	117.98
M5	186.9	188.37	196.32	181.74	182.91	190.81
M6	189.14	190.74	198.63	187.43	188.64	196.58
M7	97.81	98.70	102.71	96.19	96.80	100.78
M8	113.97	114.46	117.16	109.84	109.93	112.9
M9	93.03	93.48	95.70	92.65	92.74	95.25
M10	106.08	106.67	109.22	102.17	102.28	105.05
M11	155.50	156.61	160.24	144.53	144.82	148.59
M12A	182.91	184.08	188.39	178.07	178.23	182.98
M12B	184.01	185.26	189.20	180.03	180.19	185.00
M13	108.07	108.87	111.42	107.59	107.69	110.56
M14	148.55	149.78	153.33	139.46	139.60	143.33
M15	94.64	95.43	95.43	94.48	94.58	94.58
M16	106.07	107.06	107.06	99.53	99.64	99.64
M17	107.58	108.63	108.63	103.46	103.57	103.57
M18	113.66	114.84	114.84	107.00	107.11	107.11
TOTAL	**2489.32**	**2506.72**	**2570.32**	**2403.93**	**2410.64**	**2477.85**
TOTAL (%)	**100.0%**			**96.57%**	**96.17%**	**96.40%**

TABLE 7 – ENERGY DATA (2)

Station	**Consumption - operational (kWh)**			**Consumption - standby (kWh)**		
	Scenario 3	**Scenario 2**	**Scenario 1**	**Scenario 3**	**Scenario 2**	**Scenario 1**
M1	0.07	0.06	0.00	0.46	0.41	0.00
M2	18.44	18.62	19.40	0.82	0.72	0.00
M3	0.19	0.31	0.31	0.47	0.41	0.00
M4	0.51	0.72	1.21	0.68	0.58	0.00
M5	4.00	4.50	5.51	1.16	0.96	0.00
M6	0.54	1.16	2.05	1.17	0.94	0.00
M7	1.01	1.41	1.93	0.61	0.49	0.00
M8	3.74	4.22	4.26	0.39	0.31	0.00
M9	0.06	0.50	0.45	0.32	0.24	0.00
M10	3.51	4.10	4.17	0.40	0.29	0.00
M11	10.35	11.37	11.65	0.62	0.42	0.00
M12A	4.14	5.37	5.41	0.70	0.48	0.00
M12B	3.34	4.67	4.20	0.64	0.40	0.00
M13	0.05	0.90	0.86	0.43	0.28	0.00
M14	8.44	9.77	10.00	0.65	0.41	0.00
M15	0.01	0.85	0.85	0.15	0.00	0.00
M16	6.35	7.42	7.42	0.19	0.00	0.00
M17	3.92	5.06	5.06	0.20	0.00	0.00
M18	6.43	7.73	7.73	0.23	0.00	0.00
TOTAL	**75.10**	**88.74**	**92.47**	**10.29**	**7.34**	**0.00**
TOTAL (%)	**3.02%**	**3.54%**	**3.6%**	**0.41%**	**0.29%**	**0.00%**

By analyzing the data obtained, it can be seen that the proposed strategies in scenarios 2 and 3 were able to reduce the overall energy consumption of the line, as well as individual consumption relating to operational and working conditions when compared to scenario 1. The reduction of these rates are tied to the decrease in the number of processed parts, resulting mainly from the content-balancing actions of buffers implemented in scenarios 2 and 3, as well as the new machines allocation strategy in standby mode during the shift startup for the scenario 3.

From the data available, it is also possible to analyze the energy efficiency of different scenarios presented by indicators such as the amount consumed energy per unit produced (2), shown in Fig. 4.

$$Energy\ Consumption\ per\ part = \frac{Total\ Consumption\ [kWh]}{Total\ parts\ produced} \qquad (2)$$

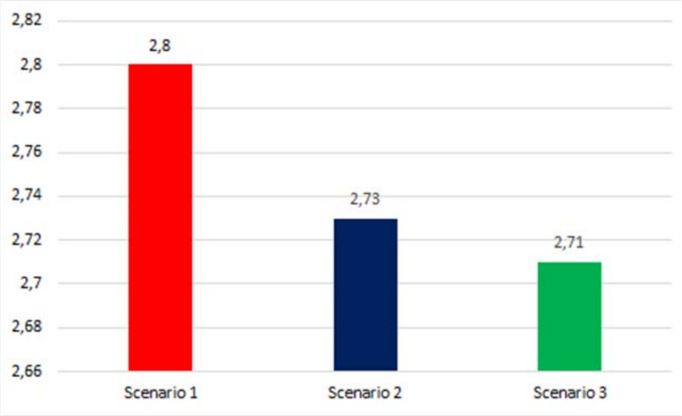

Fig. 4 – Comparison of energy consumption per unit produced between scenarios

In a complementary way, the Lean Energy Indicator proposed by [13] shows the ratio between the energy consumed in the production of salable products and the overall power consumption of the equipment, i.e. shows how the overall consumption of energy is being converted to the activities that generate value (3). Fig. 5 shows a comparison of this indicator between the three proposed scenarios.

$$Lean\ Energy\ Indicator = \frac{Consumption\ that\ generates\ value\ (processing)}{Total\ consumption} \qquad (3)$$

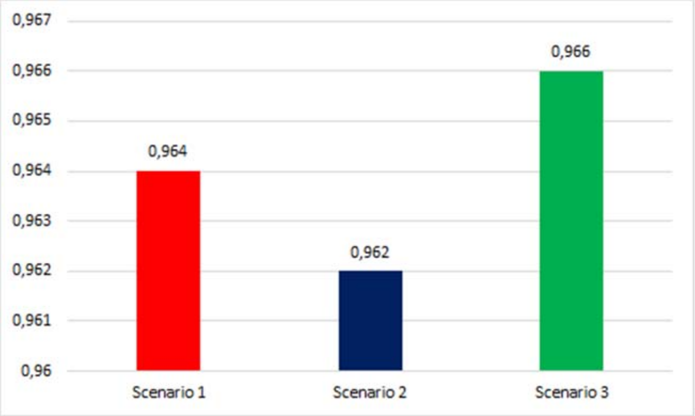

Fig. 5 – Comparative indices of Lean Energy Indicator between scenarios

The high rate achieved for all three scenarios reflects the absence of external events, such as faults, setup operations, among others, that affect the overall performance of the line. However, it is also noted that the actions taken power control allows the increase of this indicator, even in conditions already considered favorable.

This is verified in scenario 3, which presents the best result for this indicator among the scenarios evaluated, justified by the power control actions implemented during the startup of the line, which greatly reduce the consumption at a time when the equipment does not perform activities generating processing value.

As determined, scenario 3 has the lowest energy consumption among the evaluated indicators for the proposed scenarios. However, it is also necessary to draw a parallel between the gain by reducing consumption through the proposed power control strategies and production losses - one unit per shift - checked in scenario 3. Thus, the analysis of feasibility of implementation of this power control also passes necessarily through the analysis of profitability obtained per unit produced, which varies according to the assessed industry not being targeted in this study.

Regarding the demand for electric power in all scenarios assessed the maximum demand presented is 329 kW, being achieved in the periods in which all machines are in processing activity. The behavior of the electric power demand for the proposed scenarios is shown in Fig. 6.

There is, in scenarios 2 and 3, a bigger change in demand, presenting values below 200 kW. This is related to control contents of the buffers, which allocates equipment in standby mode and therefore briefly reduces the demands required for system operation. In scenario 3, one can also observe the performance of the startup control in the line in the initial minutes of the shift which allocates the equipment on standby until the arrival of the first piece for processing. While other simulations show an initial demand of 200 kW, the proposed situation starts production with a demand under 50 kW, which is increased gradually until the processing mode is achieved for all machines, at which point the system has its behavior demand equivalent to that observed in scenario 2.

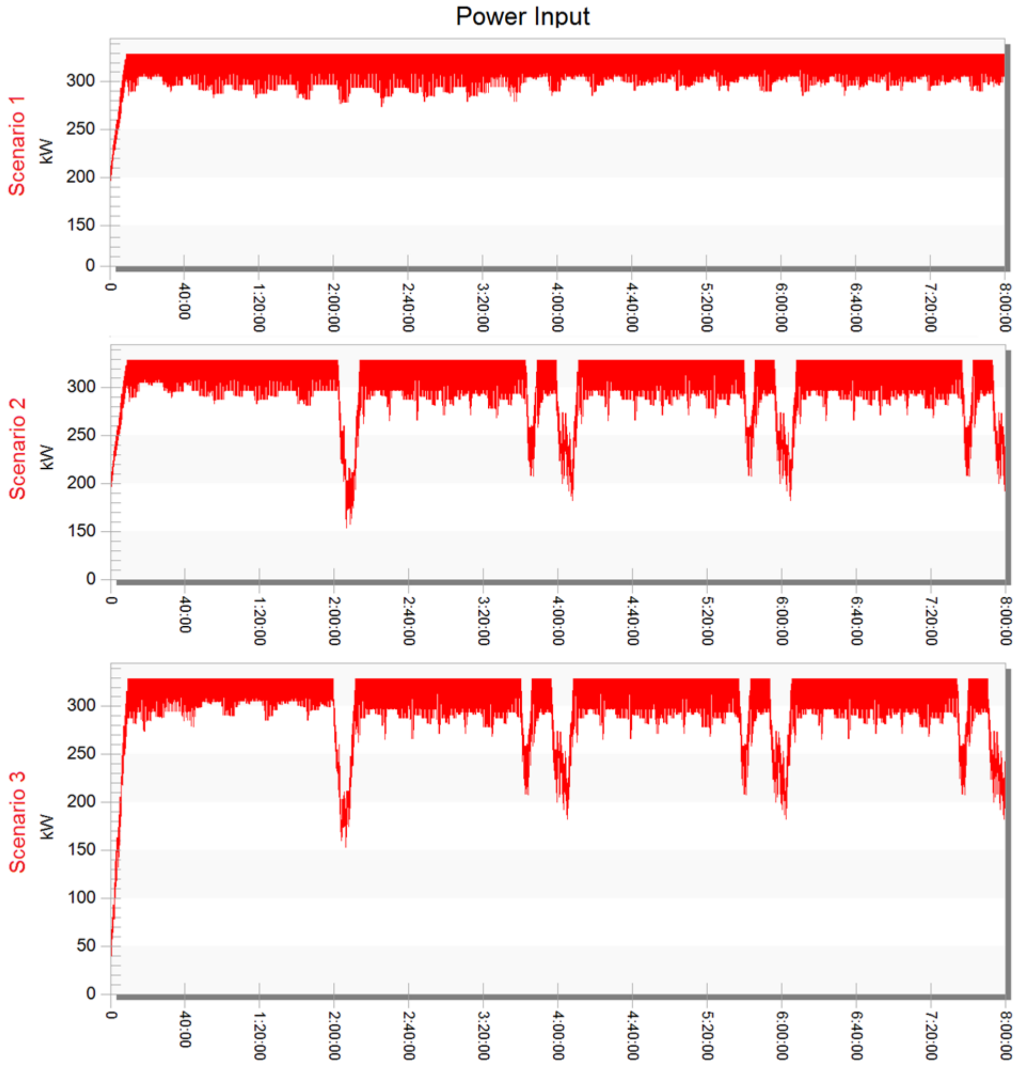

Fig. 6 – Electric power demand of comparing scenarios

According to the results and indicators obtained through the proposed scenarios, it turns out that the implementation of control strategies aimed at energy efficiency increase is feasible, even in scenarios in which final production losses are not acceptable. In cases where the reduction of energy consumption over the small loss of production is admissible exposed strategies tend to maximize the efficiency of results.

VI. CONCLUSIONS

This study had several simulation scenarios applied to the reduction of electricity consumption in an engine block production line. The entry of this new variable to the traditional production planning allows the joint analysis of manufacturing data and the energy behavior of the line through the proposed actions.

In a complementary way, the simulation using a digital manufacturing environment has proved to be an effective tool of analysis of the energy behavior of the line, allowing the presentation of the possible results from investments in energy efficiency.

The results also show that the simulation of different control actions allows not only getting a diagnosis of the current status of the facility, as well as enables the most efficient use of available resources by identifying growth opportunities in energy efficiency indicators even in systems of production already originally well designed.

Additionally, it is noted also that the use of equipment with multiple power states lets minimize consumption during periods in which the devices are idle or surplus production, thereby enhancing the results achieved through the implementation of control measures aimed at management power.

Moreover, the method not only seeks alternatives to decrease the use of electricity and their trailers costs. This work also contributes to support the implementation of sustainable practices in organizations, seeking to motivate energy efficiency indicators analysis in order to propose new solutions to reduce energy consumption in industrial plants.

Although the simulations have been performed in a specific line of production, the situations considered are typical of most industrial processes. Therefore, discussed actions can be easily adapted to other processes since the machines can be allocated in the proposed energy states.

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