Energy efficiency driven process analysis and optimization in discrete manufacturing

Alessandro Cannata
Department of Management,
Economics and Industrial Engineering
Politecnico di Milano
20133, Milano - Italy
Email: alessandro.cannata@polimi.it

Stamatis Karnouskos
SAP Research
Vincenz-Priessnitz-Str 1
D-76131, Karlsruhe - Germany
Email: stamatis.karnouskos@sap.com

Marco Taisch
Department of Management,
Economics and Industrial Engineering
Politecnico di Milano
20133, Milano - Italy
Email: marco.taisch@polimi.it

***Abstract*—Energy efficiency poses some significant challenges for most factories. To achieve fine-grained monitoring and control of energy consumption, thorough research is needed in terms of energy management models, information infrastructure and the process itself. Generally, there are three main phases that enable factory optimization: monitoring, analysis, and management. In order to reach optimal energy efficiency these steps need to be applied under the prism of energy. A coherent ICT infrastructure can provide a valuable support in terms of monitoring and control. In this paper, we focus on discrete manufacturing domain, and investigate production systems operation in terms of energy efficiency. We present a procedure which effectively supports the analysis, management, and control of discrete manufacturing systems in terms of energy efficiency and/or environmental impact. Moreover, a comparison and discussion among three different usage levels is performed through the description of different scenarios.**

I. Motivation

Energy efficiency is the target for many future factories. This comes as no surprise since approximately one third of global energy demand and CO_2 emissions is attributable to manufacturing [1]. Factories are important consumers of energy; they need to react and adapt quickly to business trends imposed by increases in energy prices. There is need to analyze on-site energy management within the factory itself, down to machine level, with the goal to optimize it. Information and Communication Technologies (ICT) can help, not only achieve better awareness on the real carbon footprint of the industry, but also better manage it and even reduce it.

Future factories will be heavily based on SOA [2], which will increase communication and collaboration among the machines, higher-level systems, the people and enterprise processes. However, any efficiency plan will need a global view and high-level orchestration. Until we reach that level, much simpler approaches can be taken by the machine itself without - or with very limited knowledge - of its surrounding operating context.

There are several steps that we see as critical in optimizing the shop floor with energy in mind:

- Monitoring: near real-time monitoring is required in order to have a fine-grained view of the energy consumption per machine;
- Analysis: timely and effective analysis of energy measurements (and their understanding/significance in a specific context) poses the basis for a strategy for energy efficiency;
- Management: once the best strategies are in place, then they must be enforced upon the infrastructure.

A cross-layer infrastructure that effectively links near real-time monitoring and management, enhancing collaboration between shop-floor and enterprise systems, is needed [3]. In this work, we focus on the individual machines, and investigate the efficiency with or without infrastructure help and knowledge. This implies that we will examine approaches for machines to reduce their energy consumption in an autonomous way without higher knowledge e.g. of their orders and also their behavior in collaborative scenarios where higher-layer knowledge is available. The focus here is on a machine-centric energy awareness and optimization.

In section II through a brief literature review the concept is introduced. Subsequently in section III we introduce the procedure for the energy efficiency analysis, and in section IV highlight the benefits coming from ICT infrastructure. In section V a case study is outlined, while some discussion elements are investigated in section VI, and finally conclusions are drawn in section VII.

II. Concept Analysis

Since eco-efficiency in the industrial domain is a key issue, much work has been performed in terms of energy analysis of production systems as literature shows. In particular, one of the main streams of research is related to Life-Cycle Assessment (LCA [4]), where the main goal is to evaluate products (or processes) in terms of their environmental impact during their whole life cycle. However, due to its aim and scope, LCA is a broad and comprehensive methodology; consequently, LCA needs to adopt high level (average) data to finalize evaluations. We argue that in order to evaluate, manage and control production systems in terms of energy consumption and environmental impact, more simple, fine-grained, near real-time and ready-to-use methods and indicators need to be adopted. These methods should follow the LCA approach (conceived for products evaluations), and should specifically focus on production systems' behavior. For example, they should be able to detect differences (in terms of environmental impact) due to changing production system dynamics (different mix of products, different production planning, etc.). In other words, we want to focus mostly on the operation phase of production systems, and define an applicable procedure for its evaluation, management and control that is influenced by or based on LCA concepts.

To define the procedure for energetic assessment of discrete manufacturing processes, we start from some interesting results found in literature. As stated by Dahmus et al. [5] and by Gutowski et al. [6], when looking at machine tools domain, the energy used for material removal can be a small part of the total energy associated with machine tool operation. This fact suggests a deeper investigation both on how machine tools are manufactured and managed. Moreover, they highlight how LCA tools, by assuming constant energy requirements, may not be effective in improving energy and environmental analysis of production systems operation. Additionally, Devoldere et al. [7] and Dietmair et al. [8] have performed analyses that highlight improvement potentials of energy consumption in discrete manufacturing machines. However, in their analyses, both papers do not explicitly consider in their procedures how reduction could be achieved. Moreover, they focus on the reduction of energy consumption due to improvement of production processes instead of production management. Finally they omit benefits that may come from an ICT infrastructure that pervasively supports the operations of production processes.

From literature review the development of production planning and control models for energy efficiency seems to be a quite unexplored field. It is therefore our aim to guide our research towards the evaluation of operation management practices that may help go towards energy efficient factories.

III. Machine-centric Energy Efficiency Procedure

We present here a procedure for the energy/emission analysis of production processes, intended to effectively support the analysis, management, and control of discrete manufacturing systems in terms of energy efficiency and/or environmental impact . This approach needs to be applicable in several discrete manufacturing scenarios; hence, the main steps are defined in a general way, in order to be flexibly adapted to each specific situation.

Looking at the discrete manufacturing domain, we made the following two assumptions in order to implement the procedure:

- *Assumption 1:* it is possible to represent manufacturing systems and their components as entities that may present different discrete states (e.g. idle, working, set-up phase, etc.).
- *Assumption 2:* for each entity (e.g. machine), it is possible to identify and evaluate each state (e.g. idle, working etc.) in terms of its contribution to the final output (i.e. the product).

The proposed procedure is partially inspired to the Life-Cycle Assessment [4] and can be considered as an evolution of the approach proposed by Devoldere et al. [7]; the main difference is that our focus is specifically on the (near real-time) control and management of manufacturing systems operation. Six main steps have been identified: objective definition, identification, evaluation, energy/emissions measurement, analysis, reaction.

1) Objective and system definition: Energy efficiency could be tackled in multiple ways (e.g. energy consumption reduction, or emission reduction) and considering different system boundaries (single machine, production line, plant, etc.). Hence, a specific objective needs to be defined, along with the definition of the system to be analyzed. The output of system needs also to be clarified.

2) Identification: Each component state of the production system is identified. The output is a model of the discrete manufacturing system made of all relevant entities (e.g. machines, conveyors, etc.) and their related states (e.g. working mode, set-up mode, idle mode, etc.).

3) Evaluation: An evaluation of each state for each entity is required. There are three possible evaluations with respect to the contribution to the final output of the analyzed production system: i.e. states that a) directly contribute, b) indirectly contribute, and c) do not contribute to it. The first type of state is defined as *valuable*, since the energy consumed for it is directly linked to the realization of the final product. The second one is defined as *indirectly valuable*, since it is needed in order to create the final product even if not all of the energy consumed is directly allocated to each product (i.e. this state should be allocated to several products in order to share the energy consumption). The last one is defined as *worthless*, since the energy consumed during that state does not contribute at all to the final product.

It is important to notice that this phase is subjective and depends on step 1. For example, the operation of a machine, apart from producing products, may be considered as a heating source when designing the general heating system of the building; in such a case, even if a machine is not producing any products, its operation could be still considered valuable to the factory ecosystem. This is true since we are considering both product and heating as final outputs of the production system.

4) Energy/emission Measurement: In this phase the fine-grained measurement of indicators such as the energy consumption or environmental impact is done. At this stage we follow a high level approach which is general enough to be applied to any type of energy/emission measurement: electrical power input, fuel/lubricants/potable water consumption, CO_2 emissions, etc. Depending on step 1, the most appropriate measure should be adopted. From now on, we consider energy measures, even if the procedure does not change for the emission measures.

Having decided the measure, an allocation of energy consumption should be carried out for each state of each entity. The model of the production system is enriched with energy consumption related to each state of each entity. The way this phase is carried out does not affect the procedure. For instance considering the electrical power input of machines, this step could be done through an analysis of the nominal data provided by machine manufacturers or by real-time measurement of the energy consumption. The difference is only on the precision and quality of the final outcome.

5) Analysis: Collected data should be analyzed and presented through a set of relevant indicators, which highlight energy inefficiencies in the production system. For example, in order to enhance energy efficiency of the production system, indicators that point out if entities stay too much in "worthless" states could be adopted. Similarly to the previous phase, the analysis could be implemented in different ways; for example it could be done in a one-shot top-down approach, or through a real-time bottom-up approach that through the record and control of a set of indicators in the ICT infrastructure, may autonomously detect inefficient behaviors of the production system.

6) Reaction: If the analysis step, points out issues or inefficiencies that should be reduced, the reaction phase needs to be carried out. This phase constitutes of a set of tools/methods that should be adopted in order to pass from the current status of the process (as-is) towards a more energy efficient process (to be). Hence, operation re-engineering needs to be carried out through:

a) Operation(s) remodeling: in this sub-phase all main relevant actions need to be considered in order to improve the defined objective. Among the possible actions, we may include: process re-engineering, changes in production planning and control policies, reconfiguration of manufacturing systems, etc.

b) Simulation of alternatives: in order to better evaluate different solutions, simulation tools are suggested to be adopted. These tools can assist in applying different "what-if" scenarios in order to increase the awareness of the decision-maker and therefore to support the effectiveness of his final decision.

c) Identification of the most efficient or optimal solution: thanks to the sub-steps (a) and (b), the decision maker would be able, at this point, to select the best available solution. This final implementation should be decided after having carried out a cost-benefits analysis.

The adaption and integration of an advanced ICT infrastructure may support future factories, better monitor, analyze, understand and take decisions that favor energy efficiency goals.

IV. Benefits coming from a cross-layer infrastructure

Still nowadays an integration gap between business IT systems and production control level exists [9]. At present, this gap is bridged through rigid proprietary solutions or through human intervention (compilation of spreadsheets, etc.). However, because of the on-going trend towards the "Internet of Things", an increasing number of embedded devices (e.g. PLC, sensors, etc.) will be able to communicate over IP, enabling dynamic near real-time information (monitored on the shop floor) to be seamlessly adopted for higher level analysis and decision making. In order to control and manage the integration needed between the production and the business layer, middleware approaches based on SOA paradigm such as [10] are needed. With this infrastructure, context-aware production control, seamless business process re-engineering, and fast reconfiguration of production lines may become possible.

From the energy efficiency point of view, a cross-layer architecture may enhance energy efficiency due to increased fine-grained and near real-time monitoring/analysis/management of devices and due to increased availability of contextual information to be adopted for complex decision making (real-time information on energy availability, environmental conditions, supply chain status, etc.). In particular, if we look at the procedure previously described, we notice that re-application of it is needed each time a change happens in the shop floor (different production scheduling, re-configuration of production lines, machine failures, etc.). Instead, thanks to the adoption of a cross-layer architecture, the different states of the machines could be continuously monitored in order to derive energy efficiency indicators. Hence, it would be possible to automatically control energy wastes due to different dynamic behavior of the production system. This is more and more important if we consider the increasing variability that is expected in future factories, due to volatile demand and enabled reconfiguration of production systems. If automatic alters could be set to advise decision makers for inefficient energy consumption, this dynamic behavior could be better controlled and the time needed to react may be reduced.

Moreover, the adoption of a cross-layer infrastructure enables production control decisions based on near real-time information about the state of production systems or on the contextual environment. This could be used to reduce energy consumption: for example it would be possible to change the scheduling of a certain machine in order to reduce the "idle" mode of other machines caused by the dynamic behavior of the system (i.e. the "idle" mode could not be detected without real-time monitoring). In energy efficient factory domain, benefits coming from a cross-layer infrastructure may enhance our capability to monitor and minimize energy consumption peaks or to change production planning depending on real-time collaboration with the future smart-grids [11]. As we witness, new models for optimization of energy efficiency should be developed, taking into consideration the ICT-enabled information-rich networked shop-floor.

V. Case Study

In this section, an example of the application of the procedure is presented, through a case study. This is not intended to be a validation on a real case, but rather an initial proof of concept on a realistic case. The case study, taken and revised from a literature review [4], [5], refers to the analysis of a production system composed by a single milling machine.

The present (as-is) scenario can be described as follows: the milling machine is (1) switched on at the beginning of each shift and (2) waits for the arrival of the next order, which provides the information on the specific operation that needs to be executed. When information arrives, (3) the correct tool is prepared on the machine. After that, (4) the machine waits until the material to be processed arrives; when the material arrives (5) it begins the proper production phase. Subsequently, (6) the tool is changed (if necessary) in order to prepare the machine for the next production, based on the information provided by the order (steps from 2 to 6 are repeated till the end of the shift). Finally, at the end of the shift the machine is switched off.

Now we go through the steps described in section III.

1) The *objective* of this analysis is the reduction of electrical consumption allocated to "worthless" states. The *system* is only composed of the milling machine and its final output is the manufactured product.
2) Through the *identification* phase we recognize four main states: activation mode (when the milling machine is turned on), idle mode (when the machine is waiting for the next product to be produced), set-up mode (when the tools is being changed), and operation mode (when the milling machine is realizing the product).
3) Since the final output, is only the product manufactured by the milling machine, the consequent states *evaluation* is outlined in Table I. Activation and set-up modes indirectly contribute to the final product (without them the product could not be manufactured), idle mode is considered "worthless", and the working mode is considered valuable.

Table I
EVALUATION OF STATES IN A MILLING MACHINE

State	Evaluation
Activation	Indirectly valuable
idle	Worthless
Set-up	Indirectly valuable
Working	Valuable

4) Since we want to analyze the electrical consumption in order to discover if "worthless" states could be reduced, we consider the nominal power input related to each state and we derive the energy consumption. In order to carry out the fourth step, we base our considerations on (elaborated) data provided by literature [4], [5], e.g. the required electrical power input related to each state (provided in Table II). Moreover, an average amount of time spent for each state is also provided. Note that the provided data are realistic, however they do not refer to any specific real case.
5) As mentioned in step 1, our aim is to reduce energy allocated to "worthless" states. Hence, an effective set of indicators could be constituted by the relative amount of energy consumed in "worthless" states ($\%_{worthless}$), the relative amount of energy consumed in indirectly valuable state ($\%_{ind-val}$), and finally in valuable state ($\%_{val}$). In simple case study the values are the following: $\%_{worthless} = 0.13$, $\%_{ind-val} = 0.34$, $\%_{val} = 0.53$. Since "worthless" states contribute significantly to energy consumption and they should be reduced (also indirectly valuable states should be considered for improvement, but for the rest of the paper we focus on "worthless" states, i.e. idle mode).
6) This is the most important step of the procedure, as possible feasible solutions are discussed. In order to reduce energy consumed in "worthless" states, in this example we focused on process re-engineering even if this is not the only feasible solution (for example, it could be possible to focus on production scheduling or else).

Table II
ENERGY MEASUREMENT OF STATES IN A MILLING MACHINE [4], [5]

State	Elect. power input	Avg. time (%)	Avg. cons. (%)
Activation	10 kW	0%	0%
idle	1.7 kW	26%	13%
Set-up	3.8 kW	39%	34%
Working	5.1 kW	35%	53%

We developed three scenarios:

1) the "as-is" scenario
2) the "isolated machine" scenario, and
3) the "collaborative machine" scenario.

The "as-is" scenario has already been described at the beginning of this section. Moreover, Figure 1 provides a representation of the process.

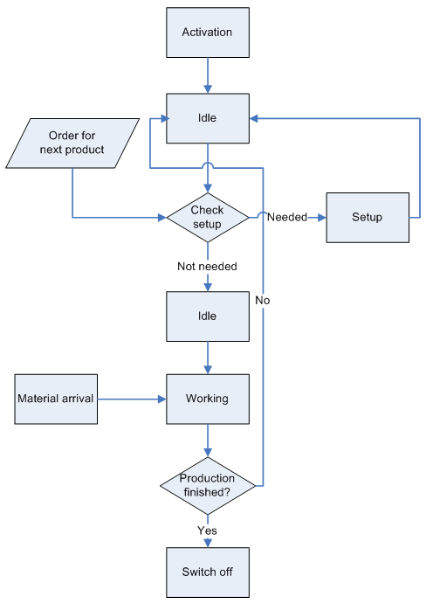

Figure 1. First scenario: as-is scenario

In the second scenario, called the "isolated machine" scenario, the milling machine is equipped with a sensor that automatically switches off the machine, if no products arrive in a predefined time delay T. Moreover, another sensor, which detects the arrival of material, is provided at the entrance of the machine in order to activate again the machine. In this scenario the reduction of "worthless" states can be obtained in an economical way (in terms of hardware needed and implementation effort). The drawback of this alternative is that other production system performances, such as lead time or throughput, could be significantly affected. This is due to fact that the production system is not controlled from a systemic point of view (no global view) but by looking only at the machine point of view (machine-centered view). Figure 2 represents the process of the second scenario.

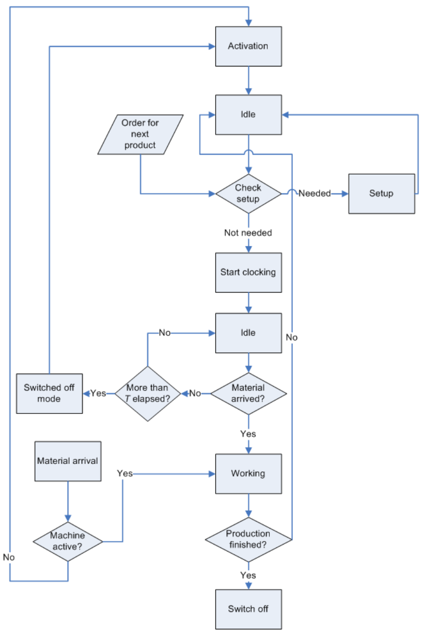

Figure 2. Second scenario: the isolated machine scenario

In the third scenario, called the "collaborative machine" scenario, the milling machine cooperates with an ICT infrastructure that is able to provide information on the system status (i.e. context). In particular, differently from the as-is scenario, after the termination of each product, the time arrival of the new coming product is checked out. If the next product arrives after a defined parameter T, the milling machine is switched off; otherwise, it returns in idle mode. In a deterministic environment where products arrive exactly when expected (deterministic process times, etc.), the parameter T can be defined as follows: $T = E_{activation} / P_{idle}$

Where $E_{activation}$ is the electrical energy requested for the activation mode and P_{idle} is input electrical power needed during the idle mode. Moreover, thanks to the ICT infrastructure that provides real-time information on the arrivals of products, in this scenario the milling machine is switched on "A" time periods before the arrival. In a deterministic environment, this parameter is the time needed for the activation of the machine, so that it will be ready when the material will arrive.

After having identified some relevant alternative solutions, they need to be assessed, by going back to some (or all) steps of the approach. In this sub-phase simulation tools are suggested in order to reduce the time and cost effort connected.

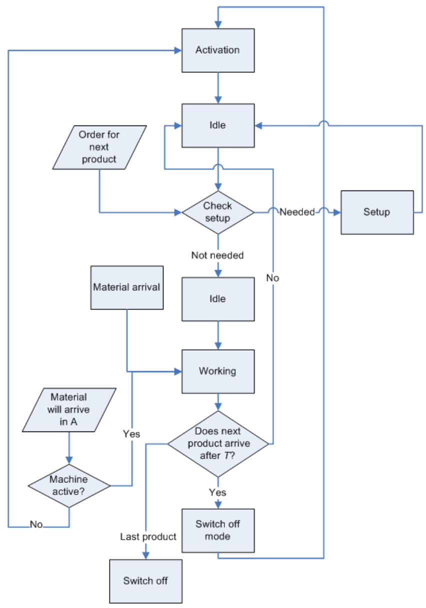

Figure 3. Third scenario: the collaborative machine scenario

Since the objective of this section is not to find out the optimal solution, but rather to present and describe the procedure, the results for each scenario have not been derived. Nonetheless, the second scenario is expected to present better energy-related performances (i.e. indicators defined in step 5), even if other performances could be affected (e.g. throughput, etc.). Finally, the last scenario is expected to show best energy efficiency performances, without affecting too much the other performances.

Finally, cost-benefits considerations are requested for this phase. As a matter of fact, the last scenario that is expected to show best results is also the most complex and costly to implement. Benefits, such as the reduction of energy consumption allocated to "worthless" states, should be compared with the cost required to implement the solution.

VI. Discussion

The procedure outlined in section III is general enough to be applied in several industries. However, there are some conditions in which this approach may become trivial. For example, when the energy associated to the activation phase is very high (i.e. switching on and off the machine is infeasible), it is clear that the approach proposed will give trivial results. However, the procedure is intended to be applied in complex and variegate manufacturing systems, where reduction of energy consumption is difficult to be obtained without the analysis of the overall system. Hence, a simple but effective approach is needed in order to find out where energy reduction opportunities are.

Moreover, in the example proposed, a static system behavior has been represented. Issues due to system dynamics were not addressed. However, if the system is composed of multiple non-deterministic machines, dynamic behaviors are involved. The approach presented could be applied also to this kind of analysis, since the basic steps remain the same. Only the adopted tool change; for example looking at a dynamic systems, enhanced production planning could be more effective (in phase 5 - reaction) in order to reduce "worthless" states (e.g. better production planning in order to avoid idle modes).

We argue that the proposed approach could be adopted to evaluate different operation management techniques and practices in terms of energy efficiency. As an example, lean manufacturing may be assessed to be compliant with the energy efficiency in some terms (i.e. waste reduction, etc.), but not in others (i.e. reduction of lot size usually increases energy consumption allocated to *indirectly valuable* states).

Due to variability of demand and due to market behavior, much R&D effort is being put in order to go towards reconfigurable manufacturing systems made of autonomous and collaborative agents. In this context, the proposed approach could be implemented in order to obtain rapid and effective information on the behavior, in terms of energy efficiency, of different configurations of the production system along with different demand needs to be fulfilled. If this is implemented in the ICT infrastructure with real-time monitoring, rapidly changing conditions could be controlled in terms of their impact on energy efficiency performance of future factories.

Another relevant on-going discussion is revolved around the impact of energy efficiency on the environment. As already evidenced by some authors [12], energy efficiency improvement could be offset in terms of environmental impact by the "rebound" or "backfire" effects, i.e. one tends to use/produce more energy efficient product/services. We argue that a direct control on the energy/emissions measurements (instead of looking only at them through cost performances), could be useful to effectively exploit the energy efficiency efforts also in terms of environmental impact.

Concerning further development initiatives, it would be interesting to extend the analysis to include unreliable machines. In that case machine failure rate could be evaluated in terms of energy efficiency. For example, one type of failure may block a machine for a period of time, during which no energy consumption is allocated. Instead, another type of failure may entail that the machine restarts requiring very high electric power input during the failure mode. These two cases would be treated differently when looking at energy efficiency performances, instead of looking at cost or time performances.

Another important direction is the investigation of trade-offs between energy efficiency and other indicators, such as time, cost, etc. With a better knowledge on these trade-offs, better scenario-specific decisions can be taken, depending on the goals and priorities of each manufacturing company.

VII. Conclusion

Energy efficiency is a key issue for future factories. Until we reach a fully cooperative and energy aware infrastructure, many issues need to be tackled. We have presented here possible ways to increase energy efficiency that rely on near real-time monitoring and control. We have taken into consideration cost-effective ones with low implementation overhead up to more complex but also possibly more efficient ones. As the factory of the future will be highly coupled with the ICT infrastructure, new possibilities for energy efficiency can be realized. These can be done at plant-level, where the global view is required, but also at machine-centric level, with the approaches we depicted. We expect that in the future a combination of both might enable us to reduce energy consumption or better optimize it.

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