23rd ABCM International Congress of Mechanical Engineering
December 6-11, 2015, Rio de Janeiro, RJ, Brazil

MINIMIZATION OF ENERGY CONSUMPTION OF A MACHINE TOOL: A MULTI-LEVEL APPROACH

Jeremi Wójcicki
Institute of Industrial Technologies and Automation, National Research Council, ITIA-CNR, Via Bassini 15, Milan, 20133, Italy
jeremi.wojcicki@itia.cnr.it

Giacomo Bianchi
Institute of Industrial Technologies and Automation, National Research Council, ITIA-CNR, Via Bassini 15, Milan, 20133, Italy
g.bianchi@itia.cnr.it

Abstract. *Energy efficiency plays an increasingly important role in modern manufacturing systems. Understanding the underlying energy consumption of machines tools and ability to predict it for a new production scenario is critical for designing high efficiency production systems. So far research was mostly focused on a single level of analysis (e.g. at component, machine, production line level). Existing models are either detailed but limited to a single component, technological process or machine or simplified as a set of discrete states, at system level, with an associated constant power use. The paper introduces a novel approach, concentrated on machine tools, which combines machine and process level analysis of energy consumption. The approach is devoted to optimize processing parameters in a multi-machine scenario for energy consumption reduction. Probabilistic production line characteristics (throughput, failure rate, part quality) are taken into consideration. The concept of intermediate energy model, a compact, simplified representation of the machine and its main sub-systems, is introduced. This type of static, direct-form energy model is intended to correlate component physical properties with the parameters which describe production mission: part features, machining strategy and processing setup. The proposed approach is demonstrated by an Experimental intermediate model of a machine tools axis.*

Keywords: *sustainable manufacturing, energy efficiency, intermediate energy model*

1. INTRODUCTION

Attention on Energy efficiency in manufacturing has been growing in last years. Scientists focused their effort several aspects concerning energy consumption of machine tools: measurement, monitoring, analysis, modelling, prediction and optimization. Five distinguishable levels of analysis in manufacturing have been identified (Duflou et al. 2012), starting from the lowest: Device/unit process, Line/cell/multi-machine system, Facility, Multi-factory system, Multi-factory system. The attention of this paper is focused around first two levels which will be referred as Machine level and Line/System level, respectively. Majority of research in the field of energy efficiency in discrete manufacturing concerns instead a single level.

At machine level there are several groups of methods: many models were created to describe in detail energy consumed during material removal process, such as work of (Draganescu, Gheorghe, and Doicin 2003) or (Stefano Borgia et al. 2014). Some models treat machine as a whole in a simplified way, e.g. defining a specific machine tool energy consumption (SEC) model (Kara and Li 2011). Hybrid energy model proposed by (T. V. Peng and Xu 2013) is an interesting alternative as it combines a parametrized components model with a state transition diagram, describing the behavior of the machine tool.

A common approach for the system level is the discrete-state analysis, in which machine tool is represented by means of a state machine diagram with a constant energy consumption related to every state. Given the probability distribution of switching from one state to another one can derive the system average energy consumption. Analysis can focus on a production cell (Dietmair and Verl 2009) or be applied to a multi-machine transfer line (Frigerio et al. 2013). This group of methods describes quantities such as supply and demand of parts (interaction with other machines in the line), machine failures, quality control rejection or energy efficiency policies in a probabilistic manner.

Relatively few publications attempt to combine knowledge of multiple levels into a single, coherent framework: (T. Peng and Xu 2014b) proposed to model energy consumption spent on each feature of the part by a multi-level approach. Another work was devoted to an on-line optimization of energy consumption (Verl et al. 2011) by hierarchical optimization loops. The potential benefits of going beyond single-level analysis can be substantial (T. Peng and Xu 2014a), especially when analyzing different production scenarios, with work pieces require a significant machining effort. In this paper a multi-level energetic modeling and optimization approach is proposed, aimed at minimizing net present cost of production, including energy cost. The considered scenario is a two machines transfer line, in which one of them must be substituted for a new model, and optimally configured for operation.

2. OBJECTIVE

Many production plant developments/deployments in Western countries are brownfield, especially when mid-volume production is considered. It means that, when the production mission changes, the same production line is reconfigured and adjusted for the requirements of new product. Commonly, some machines in such line have to be replaced, as they can be obsolete, have insufficient processing capabilities or are at the end of their life cycle. The problem lays in finding a best new machine for substitution and best parameter set (incl. processing parameters and machine management), considering also the energy factor in the overall economical evaluation.

The approach is exemplified on a minimal but representative problem: a flow line consisting of two machines working serially, with a finite buffer of defined size in between. We can assume the following information is available:

- Description of the produced parts and corresponding technological operations
- Time evolution (or probabilistic description) of parts supply and demand
- Reliability of the machines (MTTF, MTTR)
- Failure rate of quality control on the machined part
- Variability due to the human factor (operator availability etc.)
- Information about the warmup of the machine
- Predictive energy model of the machine

In this scenario we consider that only one type of parts is being produced. Production process consists of series of technological operations, assigned to one of the two machines, as depicted in the Fig. 1.

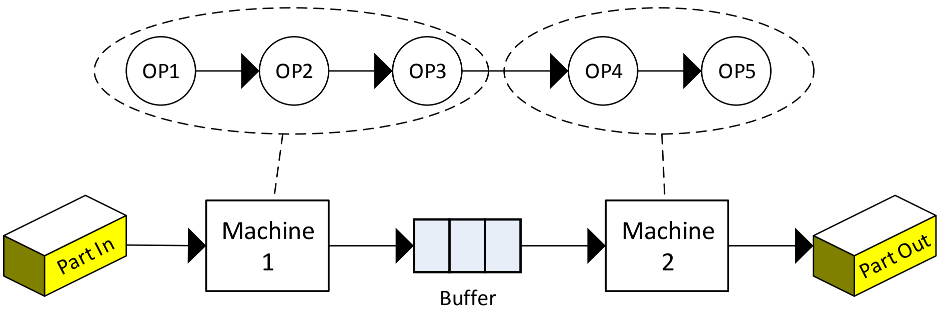

Figure 1 – Diagram of considered production line, a two way machine transfer line with finite buffer

We can assume that *Machine 1* is defined and performs operations *OP1*, *OP2* and *OP3*, which are known and defined as well. Assuming that the machine has perfect reliability, it can be considered as an ideal supply source of parts. The goal is to choose a suitable candidate for *Machine 2* and find optimal parameter set, which includes processing parameters and machine management strategy. In other words, optimization is limited to the machine that is to be replaced.

An objective function that we would like to minimize is Net Present Cost (NPC) of *Machine 2* in the plant. This indicator will discount the cost of buying a new machine and the energy costs in the investment period. Possible financial benefits coming from reduction of CO2 emission (by a reduced energy consumption) could also be included in NPC. Additional costs such as machine maintenance and tool wear have been neglected in this analysis, for simplicity reasons.

3. OPTIMIZATION PROCEDURE

The proposed approach consists of two optimization sub-problems. The first one, which is limited to the machine level, requires the derivation of the optimal Energy/Cycle time Function (ECF). This Function relates the minimal energy (with respect to the free process parameters) needed to perform the prescribed processing cycle, for a given cycle time. At each cycle time value, the set of optimal parameters, corresponding to the found minimal energy, is also saved.

This information is next passed to the system level optimizer, which will attempt to find a working point on the ECF and a machine management strategy, that would correspond to minimal energy consumption at system level. This process in not deterministic, and the optimization is affected by probabilistic distributions of supply and demand, failure rates and other factors, mentions in the previous section. The throughput of the line must be respected as well and it formulates a constraint for the optimization algorithm.

Problem is solved for every machine separately and their final score (NPC) is then compared for selection of most suitable machine (Fig. 2).

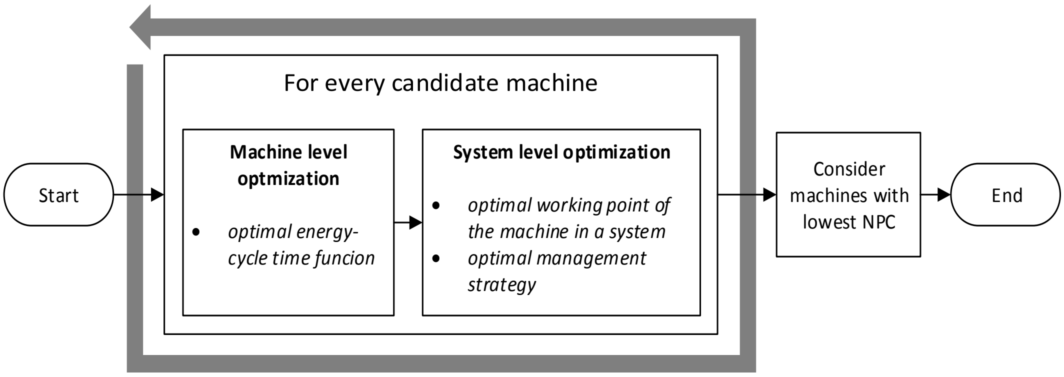

Figure 2 – overall description of NPC optimization problem

3.1 Machine level optimization

In order to compute the Energy/Cycle time Function (ECF) for a given machine and set of required technological operations, the machine energetic behavior is described by an "*intermediate energy model*". Such model is described as a function that returns energy and cycle time, given the parameters that describe the machine and the required production:

$$[E, C_t] = F(p_{part}, p_{machine}, p_{strategy}, p_{process}) \quad (1)$$

The model has four groups of arguments, respectively:

- Description of part and processing plan (operation sequence)
- Description of machine (model coefficients)
- Operation strategy (toolpath, toolset)
- Processing parameters

The first two arguments are defined and fixed for a given production mission and machine, whereas the latter two can be modified to reach the energy minimization goal. It also has to be noted that these arguments are subject to certain constraints e.g. machine capabilities, quality requirements etc. They will also affect cycle time which is critical for maintaining line throughput, as discussed in on the following.

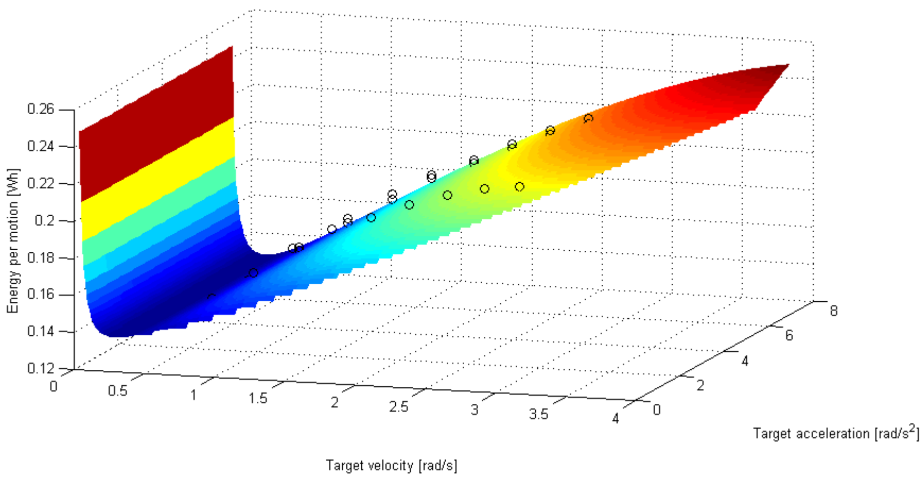

Figure 3 – Response surface of intermediate model of a rotary machine tool axis for a 180 degree motion. Energy per motion as a function of motion parameters: target acceleration and velocity. The black circles represent experimental measurements.

The approach, that will be applied to model a machine tool producing one part, is exemplified in the following considering a simple case: a machine tool axis executing a rapid motion without external forces. The energetic model relates the kinematic parameters (stroke, maximum velocity and acceleration) to the energy losses occurring in the motor and mechanical transmission. In Fig. 3 the model has been applied to compute the energy used to move the axis by a given distance, under varying velocity and acceleration. It may seem that the best choice from the energy point of view would be to operate using parameters that corresponds to the global minima of the response surface. However, choosing such parameters will also determine the cycle time, which affects the energy per part and throughput at the system level. Therefore, an ECF is a possible way to pass the information about energy together with cycle time to the system level optimizer.

In order to derive ECF, one must find of the energy per motion for every cycle time value (C_t), in a considered range. Therefore the cycle time parameter, which is being returned by the ECF, becomes a constraint for every optimization sub-problem. System level optimization will exploit the ECF to find the cycle time value that produces the global NPC.. A set of constraints on the decision variables must be taken into consideration as they express machine capabilities (e.g. operational ranges of machine components) and quality requirements (some combinations of parameters are not allowed, e.g. to avoid cutting process unstability). Graphical representation of the optimization problem is shown in Fig. 4.

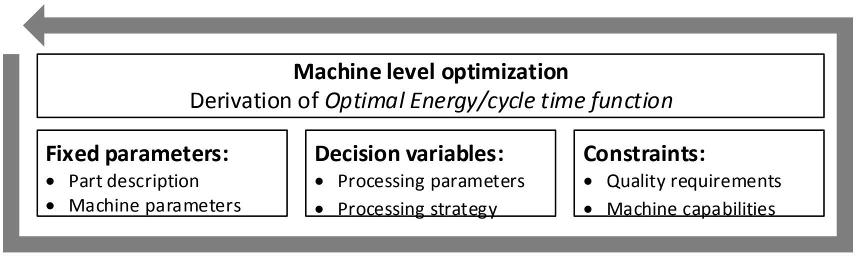

Figure 4 – Optimization problem at the machine level

Decision variables for machine level optimization include:

- *Processing parameters* indicate all variables that describe the material removal process (e.g. material removal rate, chip thickness, feed), motion of the machine (e.g. rapid motion parameters) and other parameters that describe behavior of machine subsystems and have relevant influence on either energy consumption or cycle time.
- *Processing strategies* include set-up of the machine (toolset) and tool path selection.

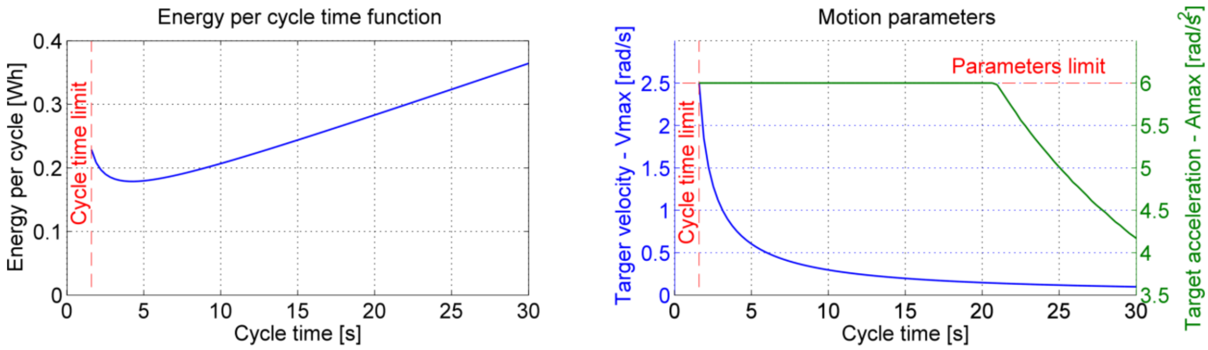

Figure 5 – Derived optimal Energy/Cycle time Function with corresponding motion parameters for a given stroke of the identified machine tool axis

Fig. 5 presents an ECF obtained as a result of applying optimization to the intermediate model (introduced in Fig. 3) of a rotary machine tool axis. The left plot indicates the minimum energy spent to execute the prescribed stroke, while the right plot reports the corresponding parameters. Parameter upper bounds are marked by the horizontal red line and translate into a lower limit of the cycle time, that corresponds to the maximum system (machine) throughput of.

3.2 System level optimization

Machine tool operation can be described as a continuous-time discrete state Markov process, with a certain finite amount of states (represented as the circles in Fig. 6). Arrows indicate a directed transition from one state to another, with a defined probability distribution of transition in time. States also have a probability related to remaining in the same state (the arrows pointing to the same state were skipped in the graph of simplicity). Staying in each state costs energy: for all states apart from processing, we have a fixed power consumption, so that the energy consumed by the state is proportional to of staying in that state. *Processing* is a special state in which the energy is given by the ECF, and is a function of cycle time. The goal of the optimization is to find minimum of energy respecting required throughput of the line (constraint). It can also be considered, that the maximum energy consumption may be constrained, to respect environmental restriction.

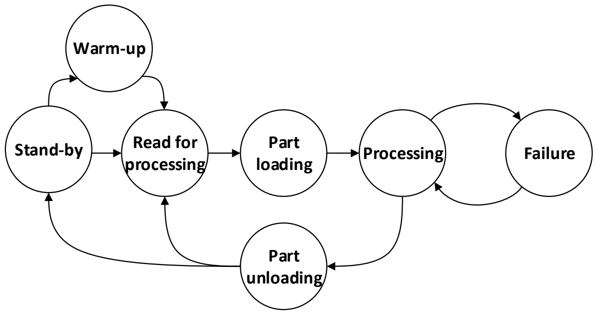

Figure 6 – Example of state diagram describing production process

A possible approach is to solve the problem for every cycle time T_c of the ECF, optimizing remaining decision variables – *part loading strategy* and *machine management* (Fig. 7). Finding the optimal decision variables will result in obtaining an optimal set of parameters corresponding to the selected point (cycle time) on the ECF.

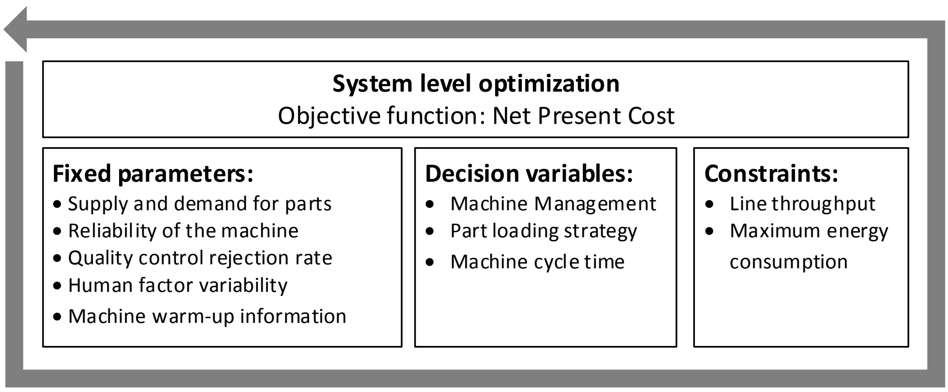

Figure 7 – Optimization problem at the system/process level

Decision variables for system? level optimization include:

- The term *Machine management* is considering energy saving policies which usually include shutting down the machine during idle or switching to low consumption stand-by modes. Usually it means shutting down the components that can be restored almost immediately and usually would not require performing any warm-up procedure.
- *Part loading strategy* indicates different modes in which parts will arrive into the machine. Either parts will arrive as soon as the machine finished machining the previous part, or they can be stored in a buffer before the machine and, to be processed in batches.
- *Machine cycle time*, which is represented as a working point of the machine in the ECF.

4. DISCUSSION

However, there is a series of issues that should be addressed, to develop the proposed methodology.

Presented optimization problem, both for the machine and system level, is subject to numerous constraints. If the considered technological process is more complex (increased amount of subsystem and operations) number of parameters together with constraints will explode. Therefore, an issue that need to be addresses is how to efficiently manage constraints or break down the main optimization problem into simpler, independent sub-problems. On more complex problems, in order to obtain a manageable ECF, a certain inaccuracy on energy estimation has to be accepted. How to manage the derived uncertainty within the framework has still to be investigated

In presented example of the machine axis, the ECF was a continuous function, however when discrete design parameters are used, this will not be the case. Therefore, attention must be paid to a proper optimization approach, able to optimize on system level using discontinuous ECF.

5. CONCLUSIONS AND FUTURE WORK

The presented framework proposes a two levels optimization of energy use: machine and system level. Such an approach gives good opportunities to evaluate a candidate machine tool considering its properties, the requested machining operations, but also the system architecture and the adopted management strategies.

Future work will mostly include further development of optimization procedures for more complex processes and machines with multiple subsystems. These is need to develop a uniform methodology for modelling energy policies (part loading and machine management) that are suitable for optimization. Final goal is to demonstrate derived approach on a representative industrial case.

6. ACKNOWLEDGEMENTS

The authors gratefully acknowledge the European Commission for its support of the Marie Curie program through the ITN EMVeM project (GA 315967).

7. REFERENCES

Dietmair, Anton, and Alexander Verl. 2009. "A Generic Energy Consumption Model for Decision Making and Energy Efficiency Optimisation in Manufacturing." *International Journal of Sustainable Engineering* 2 (2): 123–33. doi:10.1080/19397030902947041.

Draganescu, F., M. Gheorghe, and C.V. Doicin. 2003. "Models of Machine Tool Efficiency and Specific Consumed Energy." *Journal of Materials Processing Technology* 141 (1): 9–15. doi:10.1016/S0924-0136(02)00930-5.

Duflou, Joost R., John W. Sutherland, David Dornfeld, Christoph Herrmann, Jack Jeswiet, Sami Kara, Michael Hauschild, and Karel Kellens. 2012. "Towards Energy and Resource Efficient Manufacturing: A Processes and Systems Approach." *CIRP Annals - Manufacturing Technology* 61 (2). http://escholarship.org/uc/item/6bd3c6bw.

Frigerio, Nicla, Andrea Matta, Luca Ferrero, and Fulvio Rusinà. 2013. "Modeling Energy States in Machine Tools: An Automata Based Approach." In *Re-Engineering Manufacturing for Sustainability*, edited by Andrew Y. C. Nee, Bin Song, and Soh-Khim Ong, 203–8. Springer Singapore. http://link.springer.com/chapter/10.1007/978-981-4451-48-2_33.

Kara, S., and W. Li. 2011. "Unit Process Energy Consumption Models for Material Removal Processes." *CIRP Annals - Manufacturing Technology* 60 (1): 37–40. doi:10.1016/j.cirp.2011.03.018.

Peng, Tao Victor, and Xun Xu. 2013. "A Universal Hybrid Energy Consumption Model for CNC Machining Systems." In *Re-Engineering Manufacturing for Sustainability*, edited by Andrew Y. C. Nee, Bin Song, and Soh-Khim Ong, 251–56. Springer Singapore. http://link.springer.com/chapter/10.1007/978-981-4451-48-2_41.

Peng, Tao, and Xun Xu. 2014a. "Energy-Efficient Machining Systems: A Critical Review." *The International Journal of Advanced Manufacturing Technology* 72 (9-12): 1389–1406. doi:10.1007/s00170-014-5756-0.

———. 2014b. "Energy Consumption Evaluation for Sustainable Manufacturing: A Feature-Based Approach." In *2014 11th World Congress on Intelligent Control and Automation (WCICA)*, 2310–15. doi:10.1109/WCICA.2014.7053082.

Stefano Borgia, Marco Leonesio, Giacomo Bianchi, and Paolo Albertelli. 2014. "Machine Tool Energetic Simulation during General Milling Operations." In *Innovations of Sustainable Production for Green Mobility - Energy-Efficient Technologies in Production*. Chemnitz, Germany.

Verl, Alexander, Engelbert Westkämper, Eberhard Abele, Anton Dietmair, Jan Schlechtendahl, Jens Friedrich, Holger Haag, and Sebastian Schrems. 2011. "Architecture for Multilevel Monitoring and Control of Energy Consumption." In *Glocalized Solutions for Sustainability in Manufacturing*, edited by Jürgen Hesselbach and Christoph Herrmann, 347–52. Springer Berlin Heidelberg. http://link.springer.com/chapter/10.1007/978-3-642-19692-8_60.

8. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.