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Realizing energy reduction of machine tools through a control-integrated consumption graph-based optimization method

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Abstract

Industrial manufacturing has started focusing on the topic of energy efficiency already some years ago. Nowadays, even machine controls are equipped with possibilities to switch the machine into energy saving modes or even to shut it down entirely based on fixed time intervals or manually. The developed combination and modification of state-based consumption modeling with graph-based optimization theory enables the control to choose the energy-optimal state sequence for given unproductive times. The approach is presented in detail and its saving potential is demonstrated by a usage scenario from an industrial setup.

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Keywords: energy efficiency; energy optimal control; consumption modeling; operating state-based optimization; ECOMATION

1. Introduction

Industrial manufacturing has started focusing on the topic of energy efficiency already some years ago. The driving factors are rising energy costs [1], growing shortage of natural resources, green behavior for a corporate image, or ISO 14001 certification [2].

Duflou et al. [3] give an overview of saving strategies in manufacturing. Using energy-efficient components, such as electric drives or speed-controlled pumps is state of the art in new machine tools [4], and can reduce the components standby energy by up to 65% [3]. By optimizing process parameters, process power consumption can be significantly reduced (case study with reduction by 66%) [5]. Through energy optimal planning (i.e. machine tool selection) reductions in the area of 8.5% are possible [6]. Another lever of energy efficiency is to reduce the energy consumption during unproductive times while taking into account technological constraints such as the necessity to warm-up the machine to ensure production tolerances. Nowadays, machine controls are equipped with possibilities to switch the machine into energy-saving modes or even to shut it down entirely [7-8]. However, the logic to reach these saving modes during unproductive times is either based on fixed time intervals or the functionality is available on the machine's HMI for the machine operator to operate manually. So the energy-optimal setup regarding the actual duration of planned or unplanned unproductive times (e.g. setup or break times) is not considered. This leads to the open issue on how these time intervals can automatically be spent with lowest possible energy consumption.

In previous publications of the research group ECOMATION, a state-based consumption modeling approach [9], a framework for the factory-wide energy consumption control of machine tools [10] and an approach for an automated provision and exchange of energy information [11] have been introduced. The paper presents the newly developed consumption graph-based energy optimization approach to reducing the energy consumption during planned or unplanned unproductive times. The approach applies the above mentioned results and takes into account the relevant optimization constraints.

The paper starts with an overview of the developed approach and its objectives in Section 2, followed by the optimization constraints to consider for an applied optimization of a machine tool's operation in Section 3. The analysis of a machine tool's energy consumption in

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general, the state of research in energy consumption modeling and a graph-based optimization theory are shown in Section 4. The developed consumption graph-based optimization approach is presented in detail in Section 5. Its prototypical implementation is described in Section 6, and the paper is summarized with a short conclusion in Section 7.

2. Overview of the approach and optimization objectives

In industrial manufacturing, the state trajectory, which in this context means the switching of operating states, is commanded either by the worker directly at the machine control or by messages from the production planning and control (PPC) layer. The only operating state that should be considered compulsory during an operating state optimization is the production state, highlighted in red in the operating state trajectory in Fig 1. But there always exist multiple planned or unplanned unproductive times. These times, marked as *production interruptions* in the upper part of Fig 1, yield an energy-saving potential that is most commonly not fully exploited in the field. When the machine control is to reach a desired operating state, there are often multiple ways to reach this state, so the energy-optimal trajectory should be picked. When the PPC sends a message to the machine controls, that production will be suspended for a given period of time, the machine control should bridge this time with the least possible energy consumption but should be ready to operate when the time period is over. This also applies to the situation when the worker enters a probable timeframe for a production interruption on the machine's HMI. When the exact duration of an interruption is not clear, but supposed to be long, the machine control should reach its energy-optimal state on a trajectory with minimal energy consumption. The machine control should ensure

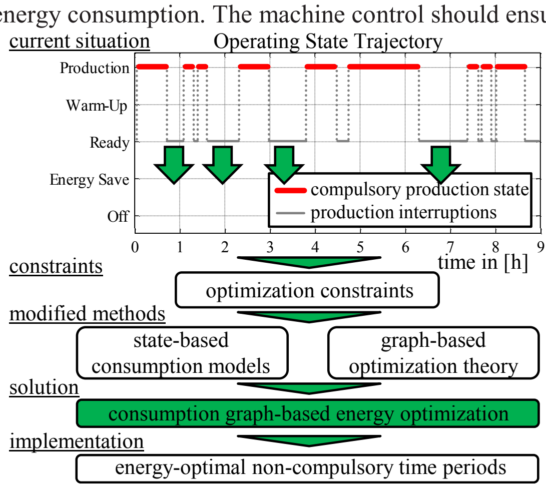

Fig. 1. Consumption graph-based energy optimization approach

that each time period is spent in the most energy-efficient state or on the most energy-efficient state trajectory. Consequently, there exist the following three objectives:

- reaching the desired state with energy-minimal operating state switches,
- reaching the desired state within a given time window on energy-minimal operating state trajectories,
- spending a given time period (e.g. maintenance) with the lowest possible energy consumption.

The approach (see Fig 1) detailed in the following reaches those objectives with respect to optimization constraints and with the application and modification of state-based consumption models and of graph-based optimization theory.

3. Relevant optimization constraints

The operation of machine tools has constraints that have to be met. The most obvious constraint is time. The compulsory production state has to be reached within a fixed, given time period. Switching between operating states takes a certain amount of time. To meet the defined production tolerances, the machine tool has to maintain a certain temperature range during production. When the machine tool remains in non-productive operating states its temperature level drops. Prior to resuming production, the required temperature level has to be reached through a warm-up, most commonly through a predefined control program. This fact constrains the trajectories that can be traveled on a given operating state graph depending on the time spent in some of the operating states.

Further constraints are the minimal and maximum times the machine control can spend in a given operating state or if a predefined remaining period is not possible at all.

4. State of research in energy consumption analysis, modeling and graph-based optimization theory

Energy consumption metering, monitoring [12] and modeling [13] are the means to analyze the energy efficiency of machine tools. The first step towards consumption reduction is the analysis of the power consumption of machine tools.

4.1. Consumption analysis of machine tools

As described by Dietmair et al. [14] and Li et al. [15], the permanent load or fixed energy consumption has a considerable share of the total energy consumption of machine tools. The power consumption depends on the operating state of the machine tool and of the sub-states of components, such as the coolant pump, the hydraulic pressure pump or cooling devices etc. [14]. Case studies by the research group ECOMATION have shown, that machine tools in industrial setups - in production lines and also with independent machine tools - are most commonly not switched off during unproductive times within shifts or during shift changes. Of course not every machine tool in the field is equipped with state of the art controls and equipment, simply because the average machine tool in the German industry is about 15-20 years old. The mentioned time periods of remaining in an idle state yield high power consumption without any productive value adding.

4.2. Consumption modeling of machine tools

In the context of ECOMATION, Verl et al. [9] show that a state-based modeling approach (see Fig 2) for calculating the power consumption of a machine tool based on its operating state trajectory is applicable on the machine control and on higher factory levels. Its simplest application would be to analyze the mean power consumption for each relevant component and define in which state it is active.

A theoretical approach to model this behavior as a graph with states and transitions was presented by Dietmair et al. [14] and slightly modified by Schmitt et al. [16]. The modification of Schmitt et al. [16] changed the management of state transitions in a way, that the transition itself costs energy instead of this transition energy being consumed by the state. Their focus lies on operations performed on the machine instead of the operational behavior of the machine itself. In both approaches, the energetic state graph of machine tools is mathematically described as tuples of states and transitions.

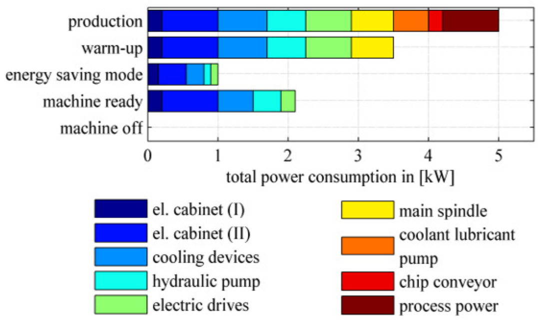

Fig. 2. State-based energy consumption model applied from [9]

Equation (1) gives the mathematical definition from Dietmair et al [14], in which T_i is the transition from state S_n to S_m, which is enabled by the logic expression C.

$$T_i = \left(S_n, S_m, C, t_{Trans}, t_{Sn,\min}\right) \tag{1}$$

The transition takes the time t_{Trans} and can only be started when the graph has previously remained in state S_n for the time $t_{Sn,min}$.

4.3. Graph-based optimization theory

In part, the solution for the mentioned optimization problems is the use of search algorithms on graphs. A graph G as defined in equation 2 consists of a set of vertices or nodes V and a set of edges E. For each edge a weight w is defined which stands for the cost or distance to overcome the edge. In the context of energy consumption optimization these costs are power input or energy consumption and time.

$$G = (V, E) \tag{2}$$

The algorithm described by E.W. Dijkstra in 1959 [17] finds either the shortest path between a start and end node or the shortest paths between a start and all other nodes of a graph. Fig 3 shows a state graph with nodes S, A, B, C and D. The arrows represent edges and the numbers at the edges represent their weights. The A*-Algorithm [17] extends the Dijkstra-algorithm by using heuristics; it finds a path from a start node to an end node with a continuous estimate of the shortest distances. During their execution, both algorithms constantly calculate and compare previously calculated distances from the start node to the other nodes in the graph. For the result of the algorithms on a state graph see Fig 3, in which S is the start node, and the green, solid arrows show the shortest path from S to every other node of the graph. For the mentioned optimization problems, the algorithms can be stopped, when the most energy-efficient (shortest) path from the initial operating state to the desired operating state has been determined.

In order to apply these algorithms, the graphs have to be represented on the computer of the machine control, which can be done in multiple ways:

The adjacency matrix for graph G with n vertices is n x n by size and each entry a_{ij} gives the weight for the edge from node i to j or is zero if there is no edge. The incidence matrix for a graph G with n vertices and e edges is n x e by size and each entry b_{ij} expresses whether an edge j leaves (value 1) or enters (value -1)

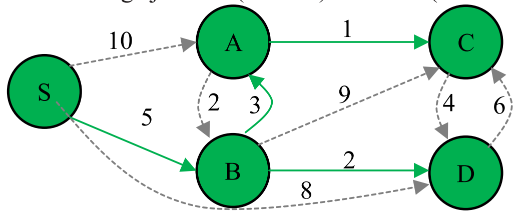

Fig. 3. State graph (shortest path as solid green line resulting from Dijkstra or A*-algorithm)

node i or if there is no edge (value 0).

The previously described representations are static and useful for dense graphs, but not flexible towards changing numbers of edges or nodes. Storing sparse graphs as adjacency lists enables graph modifications. The adjacency list representation for the graph G consists of a field with a list for each node in the graph. Each list contains all nodes that the node it represents has an edge to.

5. The developed consumption graph-based energy optimization approach

Fig 1 shows the structure, inputs and outputs of the consumption graph-based energy optimization approach. Based on the knowledge or at least an approximation of the duration of production interruptions and in combination with the state-based consumption modeling approach, the previously mentioned objectives are reachable by means of graph- or state-based optimization theories respectively. For the optimization, the following three problems can be deducted. Reaching a desired operating state on a state trajectory optimized for

- one criterion (e.g. either minimal time or minimal energy consumption),
- one criterion, but in the meantime staying within the boundary of another condition,
- one criterion and exactly fulfilling a supplementary condition.

5.1. Graph representation of energy consumption models

To apply the optimization theory on the energy consumption reduction of machine tools, the energy consumption model has to be defined as graph. Due to the fact that - in contrast to the sole graph theory - the machine tool can remain within states, the graph representation of the machine tool's energetic behavior is not identical to a common state graph. Fig 4 shows a consumption graph with five operating states for a milling machine. The operating states with a solid line are states in which it can spend time, whereas the operating states with dashed lines are not meant to remain in. The operating states in the energy consumption graph in Fig 4 are defined by a mean power input in Kilowatts. The colors of the states define their type. Red indicates the compulsory production state in which the machine control cannot remain except during production. The yellow state warm-up is not meant to remain in, except to bring the machine tool to the necessary temperature level. States the machine can spend non-productive times in are indicated in green. The arrows or edges show possible state transitions,

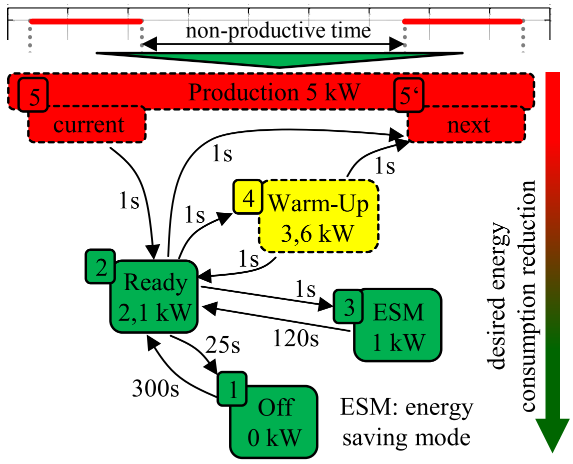

Fig. 4. Consumption graph to optimize the bridging of non-productive time between two sets of production

executed through control inputs. The numbers on the edges indicate the times that it takes to enter or leave each operating state. Shown in the graph are neither the time constraints that are applicable when remaining in an operating state, e.g. the duration of the warm-up, nor the energy cost for a state transition. Equation 3 shows the time-based adjacency matrix for the graph in Fig 4 with times in seconds. The energy cost for the state transitions is given in the energy based adjacency matrix in Kilowatts in Equation 4. The constant power consumption in each state is given in Kilowatts in vector p in Equation 5.

$$A_{time} = \begin{pmatrix} 0 & 300 & 0 & 0 & 0 \\ 25 & 0 & 1 & 1 & 1 \\ 0 & 120 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & 0 \end{pmatrix} \tag{3}$$

$$A_{energy} = \begin{pmatrix} 0 & 1{,}5 & 0 & 0 & 0 \\ 1{,}5 & 0 & 1{,}5 & 2{,}6 & 3{,}5 \\ 0 & 1{,}5 & 0 & 0 & 0 \\ 0 & 2{,}6 & 0 & 0 & 3{,}5 \\ 0 & 3{,}5 & 0 & 0 & 0 \end{pmatrix} \tag{4}$$

$$p_{statepower} = \begin{pmatrix} 0 & 2{,}1 & 1 & 3{,}6 & 5 \end{pmatrix} \tag{5}$$

With this state graph representation, the energy cost and the needed time for a given state trajectory can be computed. Modified optimization theory can be applied to the energy consumption graph for an energy-optimal operation during non-productive times.

5.2. Graph-based energy consumption optimization

The first mentioned optimization problem, reaching a desired state on an optimal path, can be solved with the direct application of either the Dijkstra or the A*-algorithm. As an example, to reach the production state (No. 5 in Fig 4) from the off state (No. 1), it is obvious that the state trajectory covers states 1, 2 and 5. The sequence 1, 2 ,4 and 5 would be another possibility for the task, but it is clearly less efficient from either a time- or energy-focused point of view. Depending on the temperature constraint though, it might be the only sequence to reach the required production tolerances, depending on the preconditions:

- time spent in the off state,
- temperature level of the machine tool,
- temperature requirements for production.

To reach the compulsory or desired operating state with least possible energy consumption within a given time period, the optimization algorithms have to be modified. The approach is divided into two parts. Firstly, the energy based graph (see Equation 4) is used to define the trajectory from the current operating state to the destination state with lowest possible energy consumption. With the time-based graph (see Equation 3) it is then checked whether the resulting state trajectory stays within the given time period. If this is the case, the solution has been found. If this is not the case, the second lowest energy consumption trajectory is checked for the time constraint and so on. To shorten this process, it could be checked first, if a trajectory exists in the time-based graph that meets the time requirements.

When the machine tool is currently processing a work piece (see operating state No. 5 in Fig 4) and the machine control receives the message, that when the work piece is done, there will be a production interruption for a given time period, this time period has to be spent with the lowest possible energy consumption, as mentioned before. The only change to an operating state that is compulsory is the one right before the expiry of the time period to reach the production state. The states or state trajectories in between are free to choose with respect to the constraints mentioned. To formulate the problem to be solved with modified graph-based theory, it is clear, that the start state and the desired destination state are equal and in this case it is the operating state production. Logically, this state has to be split temporarily into two states, as shown in Fig 4, one for the currently active production and one for the next production period that has to be reached in time. The consumption graph-based energy optimization has to find an energy-optimal path from state *5 current production* to state *5' next production* (see Fig 4) for the given time period. It defines which states should be reached and in which states the machine control has to remain and for how long.

The first task of the optimization algorithm is the calculation of the reachability of each single operating state and its distance (duration and energy cost) from the production state and vice versa. The results of this application of Dijkstra's algorithm are the shortest paths from the production state to each operating state and back. Equation 6 shows the resulting vector d_{prod} for the graph from Fig 4, in which each entry *j* gives the path length over state *j* from state 5 to state 5' (see Fig 4). For example d_{prod} shows that it takes a minimum of 123 seconds to enter the energy-saving mode (ESM) between two sets of production. This leads to the conclusion that for breaks longer than 123 seconds some waiting time could be spend in ESM.

$$d_{prod} = \begin{pmatrix} 327 & 2 & 123 & 3 & 0 \end{pmatrix} \quad (6)$$

The optimal path for a given time period is found by calculating the overall energy consumption for the state trajectories when remaining in either states 1, 2 or 3. Apart from the sole reachability, it has to be taken into account whether the machine has to undergo a warm-up process after remaining in the off state. There might be occasions, when it is cheaper to restart the machine earlier and remain in the ready state instead of warming it up.

The output of the optimization is the state trajectory with the switching signals at the given instants of time. The actual switching of operating states has to be executed by the machine control, as described by Schlechtendahl et al. [10].

6. Prototypical implementation

For the prototypical implementation the consumption graph-based energy optimizer and a milling machine's consumption graph have been implemented in c# on the control's operating system.

Fig 5 shows the main power supply of a milling machine during shop floor manufacturing. The lower part of Fig 5 represents the operating states, in this case only the states 'ready' and 'production' are reached. It can be seen, that there are multiple periods without production in which the power intake averages at about 2,1 kW compared to about 5 kW during the machining process, but without value adding. Within those time periods, energy consumption reduction methods should be applied.

For the given scenario measured in industrial manufacturing, the result of the developed optimization approach is an optimized state trajectory. The comparison between this optimized state trajectory and the common, original state trajectory is shown in the

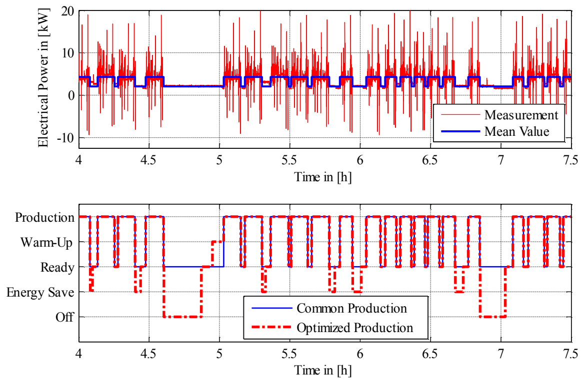

Fig. 5. Optimized state trajectory for analyzed milling machine

lower part of Fig 5. Clearly it can be seen, that the state ‘ready’ remains active for the shortest breaks, longer breaks can use the ESM and the machine can be off during the longest breaks. When the break lasts a certain time, the machine has to undergo the previously mentioned warm-up. During the analyzed two shift period of 16 hours total, the presented strategy leads to a reduction of the energy consumption of about 5 percent.

7. Conclusion

Unproductive times during manufacturing yield a high potential for energy consumption reduction of machine tools. Nowadays, energy saving modes are available on machine controls with different characteristics, but the switching to these states has to be performed either manually or in fixed time periods. The developed consumption graph-based energy optimization approach corrects this disadvantage and enables the energy-optimal spending of unproductive times. As the approach is based on mathematical representations, it is universally valid and adaptable through graph representation. The constraints enforced by the focus on the production process are observed by the algorithms. Without compromising the actual production process the presented optimization approach saves about 5 percent energy for the presented case study. This saving potential can be added as an additional measure to the saving effects stated in [3], [5] and [6] to increase the overall energy consumption reduction in manufacturing. Further work will enhance the optimizer, broaden its usage perspective and take into account the mentioned constraints with higher detail.

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