Energy-optimal programming and scheduling of the manufacturing operations

N Badea\(^1\), G Frumuşanu\(^2\) and A Epureanu\(^2\)
\(^1\)"Dunărea de Jos” University, Automatic Control & Electrical Engineering Department, Ştiinţei Street 2, 800210, Galaţi, Romania
\(^2\)"Dunărea de Jos” University, Manufacturing Engineering Department, Domnească Street 111, 800201, Galaţi, Romania

E-mail: gabriel.frumusanu@ugal.ro

Abstract. The shop floor energy system covers the energy consumed for both the air conditioning and manufacturing processes. At the same time, most of energy consumed in manufacturing processes is converted in heat released in the shop floor interior and has a significant influence on the microclimate. Both these components of the energy consumption have a time variation that can be realistic assessed. Moreover, the consumed energy decisively determines the environmental sustainability of the manufacturing operation, while the expenditure for running the shop floor energy system is a significant component of the manufacturing operations cost. Finally yet importantly, the energy consumption can be fundamentally influenced by properly programming and scheduling of the manufacturing operations. In this paper, we present a method for modeling and energy-optimal programming & scheduling the manufacturing operations. In this purpose, we have firstly identified two optimization targets, namely the environmental sustainability and the economic efficiency. Then, we have defined three optimization criteria, which can assess the degree of achieving these targets. Finally, we have modeled the relationship between the optimization criteria and the parameters of programming and scheduling. In this way, it has been revealed that by adjusting these parameters one can significantly improve the sustainability and efficiency of manufacturing operations. A numerical simulation has proved the feasibility and the efficiency of the proposed method.

1. Introduction

On one hand, in today’s manufacturing environment, all participants have to fight in order to meet the ever-changing competitive market requirements. To face this challenge, it is highly important to work in optimal conditions, and this is the reason why a very large number of researches has already been dedicated to formulate and to solve the problem of optimizing different types of manufacturing processes. As optimization criteria, the most considered are the manufacturing cost, e.g. [1, 2] and the metal removing rate (MRR), e.g. [3, 4].

On the other hand, the restrictions induced by the sustainable development concept become more and more seriously considered when addressing the manufacturing activities [5]. In connection to this, energy efficiency became an important optimization criterion [6, 7].

The expenditures for running the shop floor energy system are a significant component of the overhead expenses, hence of the manufacturing operations cost also. The natural energy transfer of the...
shop floor building has an hourly variation. A realistic assessment of the natural energy transfer from the shop floor building can be realized. Once programming a manufacturing operation, all data regarding both its duration and energy consumption are known. Most of this energy is converted in heat released in the shop floor interior and has a significant influence on the microclimate [8]. After all the current operations are programmed, they are also scheduled. If the energetic income and the operation schedule are determined, then the energy flow can be found for each manufacturing system. Various models for energy-efficient process modeling, planning and scheduling are presented in literature [9, 10]. Their main purpose is to improve the energy efficiency by realizing uniform energy consumption through a better distribution of production tasks between the existing capacities, sometimes located in different interconnected plants, but without effectively making an optimization.

Here we present a method for modeling and energy-optimal programming & scheduling of the manufacturing operations, based on a holistic approach of the entire energy consumption. It means, for that, besides the energy directly consumed in the manufacturing process, the energy embedded in the assets used in the manufacturing operation and the energy required for running the shop floor climatization system are also taken into account. The paper is structured on five sections. The next one defines the concept of energy-based optimization. The third section is dedicated to modeling of the optimization problem by defining three criteria and expressing the corresponding objective functions. The fourth section presents a numerical simulation in the case of a turning process, while the last one is for conclusions & perspectives.

2. Energy-based optimization

Let us consider a generic optimization action. It supposes four successive stages. The first one is the motivation stage, i.e. the implementation of a politics. Here the targets are defined and the actions needed to reach them are identified. The second stage is dedicated to optimization problem formulation. The decision-maker establishes, through directives, which are the optimization criteria enabling to assess the target reaching moment and, starting from here, the appropriate features that will be adjusted are chosen. In the third stage, the optimization problem is modeled. Causal relations between criteria and selected features are determined. Hereby, the criteria are used to build objective functions, having as variables the features values. Finally, the last stage means the optimization problem solving, by extremizing the objective function. The solution gives the optimal values for being assigned to the adjustable features.

We particularize below the considerations from above in the case of a generic manufacturing operation, submitted to an energy-based optimization.

Here the targets are the environmental sustainability and the economic efficiency, while the actions for reaching them are energy-optimal programming and scheduling. Three optimization criteria may be chosen as the most relevant: the energy consumption (in connection to the first target), the profit per operation (related to the second target) and the specific profit (meaning the profit obtained for each Kwh of consumed energy), as synthetic criterion, making a trade off between the two targets.
In the addressed problem, the programming action refers to processes intensity and to the choice of the assets used to fulfill the operation task. The scheduling action has in view the processes timing (assessed through the calendar time fraction used for the processes) and location (the energy efficiency of insulating the shop floor from the external environment).

3. Modeling of the optimization problem

Three criteria are considered in order to define the approached optimization problem: the energy consumption ($EC$), the profit per operation ($PO$) and the specific profit ($SP$). The optimization variables are the working process duration ($T_w$) and the scheduling effectiveness coefficient ($\beta$). The relation between criteria and variables are deducted below.

3.1. The energy consumption

The energy consumption criterion, issued from environmental sustainability policy, can be defined, at the most general level, as equation (1):

$$EC = \frac{\text{Consumed energy}}{\text{Performed work}} \quad \text{[Kwh/operation]}$$  \hspace{1cm} (1)

*Note:* Here, by operation we mean the action of manufacturing a batch of parts from same product order, consisting in a unique process performed on a given workstation. For sample, the teeth machining on a given machine tool of the 20 gears needed for a 10 gearboxes order, each gearbox including two identical gears, means an operation.

In the case of a manufacturing operation, $EC$ has three main components, equation (2):

$$EC = EC_w + EC_{h/c} + EC_e \quad \text{(2)}$$

where $EC_w$, $EC_{h/c}$ and $EC_e$ mean the energy consumptions supposed, respectively, by the working process, the shop floor heating & cooling system, and the embedded energy into involved assets (e.g. equipments, tools, devices).

![Figure 1. Workstations schedules.](image)

![Figure 2. Variation of the energy efficiency ratio ($\eta$) with the mechanical loading ($P_w$) for a given workstation.](image)

The schedules of workstations from a shop floor, drawn for a $T_{schedule}$ time interval, are presented in figure 1. Each row corresponds to a workstation. The blank cells mean performed operations of $T_{op}$ duration, while the hatched ones – inactivity periods. The coefficient $\beta^{(i)}$ reflecting the effectiveness of using the workstation “$i$” along a $T_{schedule}$ time interval is defined as equation (3):
\[
\beta^{(i)} = \frac{\sum_{j} T^{(i)}_{\text{opt}(j)}}{T_{\text{schedule}}}
\] (3)

The energy natural transfer of the shop floor building is measured through the corresponding transfer power \( P_{\text{total}}^{\text{transfer}} \), time varying. The nominal power of workstation \( i \) driving system is \( P_{0}^{(i)} \).

Note: The below presented relations will refer to a generic \( j \) operation, performed on the \( i \) workstation. From simplification reasons, we gave up to attach these indexes where needed (e.g. instead of \( T^{(i)}_{\text{opt}(j)} \) we have written only \( T_{\text{op}} \)).

If accepting an inverse proportional dependence between the working power \( P_{w} \) and the working duration \( T_{w} \) of an operation, the proportionality constant being \( K_{w} \), and a quadratic dependence between the energy efficiency ratio \( \eta \) and \( P_{w} \) (see figure 2), then \( EC_{w} \) can be expressed as equation (4):

\[
EC_{w} = T_{w} \cdot \left( a \cdot K_{w} - b \right)^{-1}
\] (4)

with \( a \) and \( b \) specific constant to be identified.

The equivalent time per operation \( TO \) can be calculated with equation (5):

\[
TO = \frac{T_{\text{op}}}{\beta} = \left( T_{w} + T_{a} + \frac{\tau_{rf}}{T_{rf}} \cdot T_{w} \right) \cdot \frac{1}{\beta}
\] (5)

where \( T_{a} \) means auxiliary time, consumed on handlings and other preparations required for effectively running the operation, \( \tau_{rf} \) – time consumed for refreshing a resource needed in the process (e.g. for replacing a cutting tool), and \( T_{rf} \) - time interval between two successive refreshes (e.g. tool durability). Between \( T_{rf} \) and \( T_{w} \) we suppose the following dependence relation, equation (6):

\[
T_{rf} = K_{rf} \cdot T_{w}^{\alpha}, \text{ with } K_{rf} - \text{constant}
\] (6)

Regarding \( EC_{h/c} \), it has different expressions for heating and for cooling. When heating is needed, the heat released by the functioning workstations diminishes the heat amount to be furnished by the climatization system \( EC_{h} \), therefore we have equation (7):

\[
EC_{h} = P_{\text{transfer}} \cdot TO - P_{w} \cdot T_{w} \cdot \eta^{-1}
\] (7)

with \( P_{\text{transfer}} \) meaning the share \( \gamma^{(i)} \) of \( P_{\text{total}}^{\text{transfer}} \) assigned to the workstation \( i \), calculated as equation (8):

\[
\gamma^{(i)} = \frac{P_{0}^{(i)}}{\sum_{i} P_{0}^{(i)}}
\] (8)

By making the required replacements, \( EC_{h} \) expression becomes (equation (9)):

\[
EC_{h} = \frac{\gamma}{\beta} \cdot P_{\text{transfer}} \left( T_{w} + T_{a} + \frac{\tau_{rf}}{T_{rf}} \cdot T_{w}^{1-\alpha} \right) - \frac{T_{w}}{a \cdot K_{w} \cdot T_{w}^{-1} + b}
\] (9)

When cooling is needed, the heat released by the functioning workstations increases the heat amount to be eliminated by the climatization system \( EC_{c} \), similarly calculated (equation (10)):

\[
EC_{c} = e \cdot \frac{\gamma}{\beta} \cdot P_{\text{transfer}} \left( T_{w} + T_{a} + \frac{\tau_{rf}}{T_{rf}} \cdot T_{w}^{1-\alpha} \right) + e \cdot \frac{T_{w}}{a \cdot K_{w} \cdot T_{w}^{-1} + b}
\] (10)
In relation (10), ε means the frigorific efficiency of the cooling system.

The consumption of embedded energy corresponding to an operation can be determined with equation (11):

\[
EC_e = \frac{1}{\beta}\left(T_w + T_a + \frac{T_f}{T_{ef}} \cdot T_w^{1-\alpha}\right) \cdot EC_{e/hour}
\]

where \(EC_{e/hour}\) is the “cost” from embedded energy point of view for an hour of workstation use. If a generic asset “\(k\)” from the set of assets required for performing the considered operation is characterized by the \(EC_{e \: \text{total}}^{(k)}\) amount of embedded energy and the \(LC^{(k)}\) lifecycle length, then (equation (12)):

\[
EC_{e/hour} = \sum_k \frac{EC_{e \: \text{total}}^{(k)}}{LC^{(k)}}
\]

3.2. The profit per operation

This criterion reflects the economical efficiency of a manufacturing operation. Its basic form is (equation (13)):

\[
PO = (\text{Price} – \text{Cost}) \ [\text{Euro} / \text{operation}]
\]

The price \(P\) of an operation can be conventionally established as a share of the product price, which means that it is a commercial choice of the producer. The cost \(C\) of an operation is calculated as:

\[
C = C_{\text{non-op}} + C_{\text{wage}} + C_{\text{refresh}} + C_{\text{energy}}
\]

In relation (14), \(C_{\text{non-op}}\) means the non-operational expenditures, namely those needed by the manufacturing process but not affected by operation programming & scheduling (e.g. the worked material cost). The other three components are the costs of wage, consumables refresh and energy, respectively and depend on operation programming & scheduling. A more detailed form of (14) is equation (15):

\[
C = C_{\text{non-op}} + \frac{1}{\beta}\left(T_w + T_a + \frac{T_f}{T_{ef}} \cdot T_w^{1-\alpha}\right)c_t + \frac{c_k}{T_{ef}} \cdot T_w + (EC_w + EC_{e/c})c_\epsilon
\]

Here, besides the already introduced notations, \(c_t\) is the unitary wage cost [Euro/hour], \(c_k\) – the refill kit cost [Euro], and \(c_\epsilon\) – the energy price [Euro/Kwh].

3.3. The specific profit

This is a synthetic criterion, making a tradeoff between the profit per operation and the afferent consumption of energy, equation (16):

\[
SP = \frac{PO}{EC} \ [\text{Euro} / \text{Kwh}]
\]

3.4. Profile of the dependence between optimization criteria and optimization variables

We further discuss, at conceptual level, the aspect of the optimization problem, in the case of the above-mentioned criteria.

If we define the process intensity \(q\) as, equation (17):

\[
q = T_{ef}^{-1}
\]

then the three objective functions \((EC, PO, SP)\) can now be considered as depending on two variables: \(q\) and \(\beta\). In figure 3, they are represented as typically looking for a given value of \(\beta\), belonging to [0, 1]
interval. It is commonly accepted that $PO$ variation shows a point of maximum, $R$, corresponding to $q_{opt}$ intensity, while $EC$ variation presents a point of minimum, $T$, for $q_{opt}$ intensity, $q_{opt} \neq q_{opt}$. 

Figure 3. The variation of $EC$, $PO$ and $SP$ criteria with process intensity ($q$) and workstation schedule ($\beta$).

Therefore, the rational domain to search for $SP$ optimal value is comprised between these two limits. For an arbitrary value $q$ inside the rational domain, we have, equation (18):

$$SP(q) = \frac{AM}{BM} = \frac{PO(q)}{EC(q)}$$

(18)

The performed numerical simulations (sampled in the next section) entitle us to state that $SP$ has a variation with a point of maximum, $S$, reached when $q = q_{opt}$. Finding an optimal value for $q$ when $\beta$ is kept constant means an optimization of programming action only. If also taking into account the scheduling, then we have to look what happens to the values of $q_{opt}^{SP}$ and $SP_{max}$ when $\beta$ is varying. It is possible that there is an optimal value $\beta_{opt}$, corresponding to which $SP_{max}$ is maximum. Hereby we define the solution of $SP$ optimization problem by the couple $(q_{opt}^{SP}, \beta_{opt})$.

4. Numerical simulation

A numerical simulation has been performed in order to test the feasibility and the efficiency of energy-optimal programming & scheduling of the manufacturing operations, as above presented. The simulation addresses the case of a turning operation consisting in a single process. The nominal cutting regime means cutting speed $v = 100$ m/min, feed rate $s = 0.2$ mm/rot, cutting depth $t = 5$ mm. The nominal values of the other parameters involved are $P = 7$ Euros, $P_w = 5$ Kw, $K_w = 25$, $T_w = 5$ min (hence $q = 12$ processes/hour), $\eta = 0.92$, $\alpha = 3.5$, $\beta = 0.85$, $\gamma = 0.1$, $\varepsilon = 0.3$, $p_{total}^{transfer} = 70$ Kw, $c_\tau = 10$ Euros/h, $\tau_{rf} = 15$ min, $c_k = 15$ Euros, $T_{rf} = 36$ min, $K_{rf} = 0.13$, $E_{ehour} = 0.5$ Kwh, $c_e = 0.25$ Euro/Kwh. These values were hypothetically adopted, in accordance with common practical processes.

The values of the objective functions $EC$, $PO$ and $SP$ were calculated with the relations from section 3, for 20 different values of process intensity $q$, comprised between 5 and 16 processes/hour, and in two cases (when shop floor climatization requires heating, respective cooling). The scheduling coefficient $\beta$ was kept unchanged. The results are presented, in graphical form, in figure 4.
As it can be observed, the optimization problem is consistent in terms of energy-optimal programming. The extreme values $EC_{\text{min}}$, $PO_{\text{max}}$, and $SP_{\text{max}}$ correspond to different values for $q$: $12$; $7.2$; respective $8.4$ [processes/hour] in heating case, and $12$; $7.2$; respective $9$ [processes/hour] in cooling case. The percent of losses (referred to the optimal point), which appear if working with process intensity different from the optimal ones, define the efficiency of energy-optimal programming & scheduling. Their values, calculated after each optimization criterion, are presented in figure 5.

![Figure 4. The process intensity influence onto objective functions values.](image1)

![Figure 5. The efficiency of energy-optimal programming.](image2)

One can easily notice that the losses can reach very significant levels if the action of energy-optimal programming is not considered. For example, $SP$ can be up to 40% smaller if the process intensity is too low, or even worse, up to 100% smaller if the process intensity is too high relative to the optimal one (both situations in the heating case).

5. Conclusion & perspectives

By starting from one of the main requirements of the sustainable development concept – the energy efficiency increase, this paper presents a method for modeling and energy-optimal programming & scheduling the manufacturing operations. It lays on a holistic approach of the energy consumption, including components neglected up to now, despite being significant.

In the mentioned purpose, the concept of energy-based optimization was firstly introduced. Then, the optimization problem was modeled by choosing as optimization criteria the energy consumption, the profit per operation and the specific profit, and as optimization variables – the operation working duration and the scheduling effectiveness coefficient. Detailed expressions for the corresponding
objective functions were deducted and the main aspects of the optimization problem were discussed, at conceptual level.

The feasibility and the efficiency of energy-optimal programming & scheduling of the manufacturing operations were both tested by running a numerical simulation in the case of a turning operation consisting in a single process. The results are convincing and they show an important potential of improving the manufacturing operations efficiency by applying the energy-optimal programming & scheduling.

Regarding the considered simplifying hypothesis (e.g. see relation (6)), they are suitable to machining operations case, but it should be noticed that they can be generalized to most of the other types of manufacturing operations (welding, forming, casting etc.).

The presented approach of energy-based optimization may seem affected by limitations, and it really is, but the limits can be pushed out in future works, by addressing to an extended optimization area (operations consisting in more than one process, groups of operations), to multi-criteria optimization or to generalized optimization algorithms.

Acknowledgement
The authors acknowledge the use of the research facilities developed by RO-054 Project, financed through EEA Grant 2009 program, in performing the research presented in this paper.

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