The relation between the shop floor energy system and the manufacturing process optimality

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Abstract. Nowadays, the overhead expenses are a significant component of the manufacturing cost. The expenditures occasioned by running the shop floor energy system are one of the most important among the overhead expenses. However, the manufacturing process optimization actually does not take into account these expenses. More than that, the expenses for running the shop floor energy system are not constant, varying after the external environment seasonal conditions, and they are depending on several issues, like the building’s energetic exchange with its environment, or the loading degree of the machine tools from the shop floor. This paper approaches the relation between the shop floor energy system expenditures, on one hand, and the manufacturing process optimality, on the other hand. A case study, revealing the influence of the shop floor energy system on the manufacturing cost-optimal solution is also included.

1. Introduction
In today’s manufacturing environment, all participants have to fight in order to meet the ever-changing competitive market requirements. To reduce the manufacturing cost, to increase the productivity and to enhance the manufactured products quality, it is highly important to work in optimal conditions. For this reasons, a very large number of researches has already been dedicated to solve the problem of optimizing different types of manufacturing processes. The practical problems’ diversity issued many kinds of approaches. The differences between these approaches are mainly regarding the optimization target (the objective function definition), the manipulated variables choice, or the method used for solving the optimization problem.

The manipulated variables are, most frequently, the cutting regime parameters [1, 2, 3], but also the number of passes [4], the driving motor power [5], or the grit size (of abrasive tools) [6]. Despite the fact that the overhead expenses are a significant component of the manufacturing cost, and the expenditures occasioned by running the shop floor energy system are one of their most important elements, we did not find anywhere an approach considering them, when the manufacturing cost is the objective function of the performed optimization.

It should be noticed that, in a country like Romania, where the difference between the monthly average temperatures from January and July is close to 30 ºC [7], the expenses for the shop floor climatisation are very significant, with a high variability during the year. Therefore, it easy to presume that they should have an important impact on the manufacturing cost, if considered, also inducing a seasonal fluctuation to it.

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Regarding the paper structure, the next section is dedicated to problem formulation. The third part suggests a new expression for the objective-function used for performing the manufacturing cost optimization, which takes into account the expenses for shop floor climatisation. The fourth section includes a case study, in order to prove the relevance of the new approach, while the last part of the paper presents the main conclusions.

2. Problem formulation

As it can be noticed in the dedicated literature, the manufacturing process optimization is performed, in practice, by selecting, from the beginning, the machine tool, the cutting tool and the other assets required to perform the considered process. Only the technical aspects are considered in this purpose (e.g. the needed power, the dimensional range etc.), while the subsequent optimization does not extend over this category of elements involved in manufacturing.

The manufacturing process optimization regards, mainly, the cutting regime parameters (the cutting speed, \(v\), the feed rate, \(s\), and the cutting depth, \(t\)), as independent variables of the optimization problem. In fact, \(t\) is not, effectively, an independent variable, because its value depends on the thickness of the material layer to be detached, and on the dimensional corrections that have to be done in order to achieve the dimensional target. Regarding \(s\), it is matter of course that its maximum possible value is optimal, but this is limited by the required roughness of the machined surface. The only one from the cutting regime parameters, which may be freely varied, is the cutting speed (although even in its case, the instability risk gives restrictions to be considered).

In this paper, we suggest that, if the manufacturing cost is the optimization criterion, then the objective-function should have a new expression, which also consider the expenses of the shop floor energy system. Therefore, some new parameters will become independent variables to be considered for finding the cost-optimal solution of the manufacturing process – for example, the building energy class, the loading degree (in time and space) of the machine tools, or the ratio between the used versus installed power of the machines driving motors.

In other words, the paper targets to reformulate the manufacturing process optimization problem, by analytically emphasizing the overhead expenses for the shop floor climatisation in the expression of the objective-function (meaning the manufacturing cost) and, consequently, by considering new independent variables, relevant for the energy system expenditures.

The paper also aims to assess the relevance of the new approach. Hence, by running a case study, we have determined the impact on the manufacturing optimization of the expenses issued by the shop floor energy system. More precisely, we have studied the variation of the manufacturing minimal cost depending on the exterior environmental conditions and on the new, above-mentioned independent variables.

3. New expression of the objective-function

3.1. Current form of the manufacturing specific cost

By synthesizing the up to date approaches regarding the manufacturing cost calculation, in specific form (referred to the volume of detached material), we may accept, in principle, the following relation:

\[
C_i = \sum_{n=1}^{\text{asset life cycle}} \left( Q_i \frac{T_n}{T} \left[ 1 + k + \frac{\tau_w}{T} \right] + \frac{c_i}{T \cdot v \cdot s \cdot t} + \frac{c_r}{T \cdot v \cdot s \cdot t} + c_m + c_e \cdot C_{\text{energy}} \right)
\]  
(1)

In relation (1), the first term gives the specific cost fraction issued by the use of the needed assets. Here \(Q_i\) means the value of the \(i^{th}\) asset, from the \(n\) needed to run a considered process, \(T_i\) – the \(i^{th}\) asset life cycle, \(k\) – the ratio between the auxiliary and machining times involved by the process, \(\tau_w\) – the time for worn tool changing, \(T\) – the tool durability, and \(v, s, t\) – as we already mentioned, the cutting regime parameters.

The second term reflects the share of the cutting tool cost. Besides the already specified notations, we have \(c_i\) – the wage specific cost (referred to time) and \(c_r\) – the tool expenditure between two consecutive tool changes.
The third term refers to the wage cost, the fourth is the specific cost of the detached material (referred to its volume), while the fifth gives the consumed energy cost. Here \( c_{se} \) means the specific energy consumption (referred to the volume of detached material) and \( c_{energy} \) – the energy price.

3.2. Shop floor microclimate

Running a manufacturing activity requires ensuring a living microclimate inside the space where this activity takes place, no matter of the exterior conditions. We are referring, mainly, to the temperature fluctuations, which in many cases are very significant. This task is covered by the shop floor energy system and it produces costs that are, usually, included in the overhead expenses category.

There are statistic indicators, for example the specific annual consumption, which are giving the annual energy consumption occasioned by covering the various functions of the residence according to the total floor area. This indicator might be also assimilated in the shop floor case. The annual consumption results by multiplying the total floor area with the value of the specific annual consumption. Depending on how global the estimation is, one may distinguish between several cases, which differ in that the evaluation is carried out or not for each function of the residence, separately and in that the evaluation is carried out or not for each form of energy, distinctly.

We should also notice that specific annual consumption of energy for climatisation purpose is highly depending on the building energy class – see table 1, [8].

| Energetic class | A  | B  | C  | D  | E  | F  | G |
|----------------|----|----|----|----|----|----|---|
| Heating annual specific consumption [kWh/m\(^2\) year] | 70 | 117 | 173 | 245 | 343 | 500 | >500 |
| Cooling annual specific consumption [kWh/m\(^2\) year] | 20 | 50 | 87 | 134 | 198 | 300 | >300 |

3.3. Specific cost formula when analytically emphasizing the overhead expenses for the shop floor climatisation

We further suggest a modified form of the relation (1) in order to define a new objective-function, which might be used for optimizing the manufacturing process, if considering the expenses for running the shop floor climatization system.

First of all we expressed the specific cost for climatization as:

\[
C_{cel} = \frac{A(1 + k + \tau_{et}/T)}{n_{ma} \cdot t_c \cdot k_d} \cdot \frac{c_{energy}}{v \cdot s \cdot t}
\]  

In relation (2), \( A \) means the monthly amount of energy needed for heating / cooling (depending on the season and on the energy class of the building hosting the shop floor), \( n_{ma} \) – the number of machine tools from the shop floor being in duty, \( t_c \) – their scheduled functioning time, in a month (depending on the number of working days and on the shifts number), and \( k_d \) – a coefficient reflecting the ratio between the machining effective time and \( t_c \).

Then, we should notice that in the months when heating is needed, the energy consumed in the manufacturing process, finally dissipated as heat, diminishes the amount of energy required for heating the shop floor. At the same time, in the months when heating is no needed, the heat resulted from the manufacturing process becomes an additional load for the shop floor cooling system.

Finally, because the fourth term from the specific cost formula is a constant, while the first has a low variability, we pulled them out from the definition relation of the objective-function, in order to give it the maximum possible relevance.

In conclusion, we are suggesting the following forms of the objective-function, in order to be used for optimizing the manufacturing process, relative to the specific cost criterion:
\begin{equation}
C_s = \frac{r_{se} \cdot c_z + c_e}{T \cdot v \cdot s \cdot t} + \frac{c_e}{v \cdot s \cdot t} \cdot \frac{A(1 + k + r_{se} / T \cdot k_d)}{n_{mt} \cdot t_c \cdot k_d} \cdot c_{energy}, \tag{3'}
\end{equation}

in the months when the shop floor energy balance shows that heating is needed, while
\begin{equation}
C_s = \frac{r_{se} \cdot c_z + c_e}{T \cdot v \cdot s \cdot t} + \frac{c_e}{v \cdot s \cdot t} \cdot \frac{A(1 + k + r_{se} / T \cdot k_d)}{n_{mt} \cdot t_c \cdot k_d} \cdot c_{energy} + 2 \cdot c_{se} \cdot c_{energy} \tag{3''}
\end{equation}
in the months when shop floor cooling is required.

We must also specify that relations (2), (3') and (3'') are not very specific and are not expected to produce precise results if applied in practice. In reality, in a shop floor there are different types of machine tools, their working times are not uniform etc. However, these formulas enable to perform a relevant case study, while if its results will be considered as significant they could be further customized for solving concrete optimization problems.

4. Case study

We further present a case study regarding manufacturing optimization, if the new objective-function is considered. It was realized by performing a numerical simulation for a hypothetical shop floor, with the help of some original applications developed in MatLab.

The targets of the case study were:

- To reveal the impact of the expenses introduced by the shop floor energy system onto the manufacturing specific cost.
- To assess the influence of the external temperature seasonal fluctuation on the solution of the manufacturing optimization problem.
- To investigate the relevance of the newly considered independent variables (the building energy class, the \( k_d \) coefficient, the percentage of using the machine tool installed power).
- To find the sensitivity of the objective-function to some of the most important independent variables (feed rate, cutting depth, degree of effectively using the scheduled functioning time).

The hypothetical shop floor considered has \( n_{mt} = 25 \) turning machines, working in a single shift of 8 hours, meaning \( t_c = 14400 \) minutes in a month, with \( k_d = 0.5 \). Shop floor surface is of 432 m\(^2\).

The monthly consumption of energy for the shop floor climatisation was calculated on the base of the specific consumption of energy, statistically measured in Galați country case [8]. The results, depending on the building energy class, are presented in table 2.

| Table 2. The energy for shop floor climatisation, A, depending on building energy class. |
|---------------------------------------------------------------|
| Heating | Monthly energy consumption [kWh] |
|---------|----------------------------------|
|         | A  | B  | C  | D  | E  | F  |
| Jan     | 6345 | 10605 | 15681 | 22208 | 31091 | 45321 |
| Feb     | 5410 | 9043 | 13371 | 18936 | 26511 | 38646 |
| Mar     | 4185 | 6995 | 10343 | 14648 | 20507 | 29893 |
| Apr     | 2150 | 3593 | 5313 | 7524 | 10533 | 15354 |
| May     | 415  | 694  | 1027 | 1454 | 2035  | 2967  |
| Jun     | 0    | 0    | 0    | 0    | 0    | 0    |
| Jul     | 0    | 0    | 0    | 0    | 0    | 0    |
| Aug     | 0    | 0    | 0    | 0    | 0    | 0    |
| Sep     | 62   | 104  | 154  | 218  | 305  | 445  |
| Oct     | 2025 | 3385 | 5005 | 7088 | 9923  | 14464 |
| Nov     | 4050 | 6769 | 10009 | 14175 | 19845 | 28929 |
| Dec     | 5597 | 9356 | 13833 | 19591 | 27427 | 39981 |
The specific consumption of energy for running the generic manufacturing process has been determined by using the Curve Fitting Tool from MatLab soft, applied to identify the curve passing by a number of points determined by experimental measurements in the case of a turning process.

In figure 1 it is presented the manufacturing specific cost variation depending on the cutting speed, when the shop floor is of $C$ energy class building.

![Image](image.png)

**Figure 1.** The new approach impact on the specific cost.

The results were obtained by running a MatLab application that uses (3’) and (3’’) formulas, where all the parameters, excepting $v$, were considered constant. The input values were: $s = 0.2 \text{ mm/rot}$; $t = 3 \text{ mm}$; $\tau_{sp} = 1 \text{ min}$; $c_t = 0.15 \text{ Euro/min}$; $c_m = 20 \text{ Euro/dm}^3$; $k = 1$; $k_d = 0.5$; $c_{\text{energy}} = 0.15 \text{ Euro/kWh}$. The tool durability was calculated, with the well-known Taylor formula, depending on the cutting regime parameters.

The chart from figure 2 presents the minimum manufacturing specific cost and its corresponding cutting speed $v_{ec}$, on each month of the year, according to the new approach, when the shop floor is of $D$ energy class building. The values were determined by running the same application of above, with the same input constants.

The chart from figure 3 illustrates the influence of the shop floor energy class on the minimum specific cost, in the extreme months (regarding climatisation need), January and July, according to the
new approach. The chart from figure 4 shows the influence on the minimum manufacturing specific cost and its corresponding cutting speed of the degree of using the machine-tool installed power (reflected by the cutting regime intensity), in January. By low cutting regime intensity we meant \( s = 0.1 \, \text{mm/rot} \) and \( t = 0.5 \, \text{mm} \), by medium – \( s = 0.2 \, \text{mm/rot} \) and \( t = 3 \, \text{mm} \), and by high – \( s = 0.3 \, \text{mm/rot} \) and \( t = 7 \, \text{mm} \). The chart from figure 5 presents the influence, on the same variables, of the degree of effectively using the scheduled functioning time \( (k_d \text{ coefficient}) \), also in January.

For finding the objective-function \( C_s \) sensitivity to the independent variables \( I_v \), defined as:

\[
S_{I_v} = \left| \frac{\partial C_s}{\partial I_v} \right| \cdot 100, \, [%]
\]

we firstly gave a variation of \( \pm 25 \% \) to three of the most important independent variables \((s, t \text{ and } k_d)\) and then we determined \( C_s \) relative variation, corresponding to this. Thus, we found \( S_s = 55.1 \% \) when the maximum shop floor heating is needed (in January) and \( S_t = 43.7 \% \) when the maximum shop floor cooling is needed (in July). We also found \( S_{k_d} = 47.8 \% \) (in January) versus 46.4 \% (in July) and \( S_{k_d} = 16.3 \% \) (in January) versus 9.8 \% (in July).
5. Conclusions
In this paper, we have suggested a new expression of the objective-function used for the manufacturing cost minimization, which consider also the expenses of the shop floor energy system. Therefore, some new parameters were considered as independent variables for finding the cost-optimal solution – the building energy class, the loading degree (in time and space) of the machine tools, or the ratio between the used and the installed power of the machines driving motors.

The performed case study entitles us to conclude that:

- The expenses of the shop floor energy system represent an important share of the manufacturing cost and because of that, they have impact on manufacturing process optimality (e.g. on the cost-optimal cutting speed).
- Moreover, the optimality is significantly influenced by the season (the external temperature fluctuation) as well as by the shop floor energy class.
- The new objective-function has a noticeable sensitivity to the feed rate, cutting depth and to the degree of effectively using the scheduled functioning time.

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