A Review on Optimization of Manufacturing Process Performance

Cezarina Afteni and Gabriel Frumuşanu

***Abstract*—In this study is present a systematic analysis of already published works on formulating and solving optimization problems concerning manufacturing process. Analysis it was performed on two levels, namely: planning and scheduling of manufacturing process. They were considered: type of optimization (mono-criterion or multi-criteria); objective function (the energy consumption, the manufacturing costs, the productivity, the manufactured surface roughness); methods of solve (Genetic Algorithms GA, Particle Swarm Optimization PSO technique, Artificial Neural Networks ANN). The main purpose of this study it is to substantiate a new approach to optimization problems. The proposed approach is of holistic type, based on integrated process planning and scheduling (IPPS) and defines new performance indicators, to be adapted to market current requirements.**

***Index Terms*—Manufacturing optimization, manufacturing process, process planning and scheduling, performance indicators.**

I. Introduction

To cope with fierce competition exacerbated by globalization, companies seeking to improve their manufacturing processes, obtain higher quality products, manufactured at a competitive price, in increasingly restrictive terms of environmental impact, production costs, and specific consumption of materials.

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.

In recent years, numerous studies on the issue of optimizing manufacturing processes have been developed.

This study presents a critical analysis of the current status of already published research on how to formulate and solve optimization problems in the case of manufacturing processes. It was performed on two levels, namely: planning and scheduling of manufacturing process.

In the analysis were explored: optimization type (uni-criteria or multi-criteria); objective function (the energy consumption, the manufacturing costs, the productivity, the manufactured surface roughness); methods of solve (Genetic Algorithms GA, Particle Swarm Optimization PSO technique, Artificial Neural Networks ANN).

The rest of the paper is organized as follows: section II provides a literature review related to the optimization of manufacturing processes, there are presented variables and restrictions for cutting processes. In section III are presented studies that addressed the issue of manufacturing processes performance being described specific performance indicators of industrial processes. In Sections IV and V is developed a critical review of planning and scheduling optimization concerning the manufacturing process, as reflected in published research up to date. Finally, Section VI presents the study's conclusion and future research directions.

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II. Manufacturing Optimization Processes

The optimization, in general, is the activity of selecting, from the possible solutions of a problem, the best one, which is assessed after a predefined criterion.

An optimization problem supposes three components:

1. The objective function, to be extremized:

$$\min, \max f\left(X\right), x \in R^m, \tag{1}$$

2. The variables vector , X

$$X = (x_1, x_2, ..., x_m), \tag{2}$$

3. The restrictions, having the form

$$g\left(X\right) \leq 0, \text{ restrictions of inequality,} \tag{3}$$

or $$h\left(X\right) = 0, \text{ restrictions of equality.} \tag{4}$$

For different processing methods (cutting, plastic deformation, welding, sintering, etc.) optimization problem has specific forms. For example, in the case of cutting, the manufacturing process can be modeled as a function of the following variables x_i:

- Tool geometry: tool constructive angles (rack angle γn, approach angle ϰr, angle of deflection λT, corner angle εr, tool cutting edge angle βn, normal angle of clearance αn, etc.).
- Cutting regime parameters: v - the cutting speed, s - the feed rate, t - the depth of cut.
- Cutting tool materials (mechanical properties).
- Work piece material (mechanical properties).
- The restrictions in cutting process optimization are:
- Maximum allowable load of machine-tools components (mechanical, thermal, chemical, tribological)
- Processing accuracy, which must conform to the technical specifications of the product
- The surface roughness, processed as specified.
- Maintaining stability, the vibrations arising in the cutting process have a major impact on quality of processed surface, dimensional accuracy and the integrity of technological system elements

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- Temperature in the cutting zone, due to the influence of the heat on the strains, tool resistance, process precision, tool dimensions, chip dimensions, roughness of the processed surface.

III. Performance of Manufacturing Processes

In a world of globalization and technology, the indicators through which the performance of manufacturing process is characterized have evolved and diversified.

The traditional performance indicators are: the productivity, the cost, the energy consumption.

- *The productivity* is desirable to reach largest value, being limited by cut material processability, cutting qualities of the tool, organization of production, quality and degree of automation of the technological systems, qualifications, skills and experience of operators. The productivity can be expressed by the following relations:

$$Q = v \cdot s \cdot t, \tag{5}$$

or

$$Q = \frac{k}{T_m}, \tag{6}$$

where v - means the cutting speed, s - the feed rate, t - the cutting depth, k - constant, T_m - the manufacturing time.

- *The cost* - because current trend of all companies is to reduce processing costs, using optimized working conditions they obtained: processing with minimal expenses, reduced labor, lower power consumption as, tools and materials.

The cost can determined with the relation [2]:

$$C_s = \sum_{i=1}^{n}\left(\frac{Q_i}{T_i}\right)\cdot\left\lfloor 1 + k + \frac{\tau_{sr}}{T}\right\rfloor\cdot\frac{1}{v\cdot s\cdot t} + \frac{\tau_{sr}\cdot c_\tau\cdot c_s}{T\cdot v\cdot s\cdot t} + \frac{c_\tau}{v\cdot s\cdot t} + c_{mater} + \frac{k_{energy}\cdot c_{energy}}{v\cdot s\cdot t}, \left(\frac{Euro}{cm^3}\right) \tag{7}$$

where Q_i - the value of the "i^{th}" asset the processed quantities, T_i - the "i^{th}" asset life cycles, c_τ - the wage specific cost, c_s - the tool expenditure between two consecutive tool changes, τ_{sr} - the time for worn tool changing, c_{mater} - the specific cost of the detached material, k_{energy} - the energy coefficient, c_{energy} - the energy price.

- *The energy consumption*, in order to improve the energy efficiency the companies started to define strategies to identify the energy flows which are scattered, to set the most profitable measures within development projects to eliminate losses, to estimate costs and profits, and find the most suitable methods of achieving cost savings in terms of energy consumption versus impact on the environment. The energy consumption can be determined with the relation [3]:

$$EC_w = T_w\cdot\left(a\cdot\frac{K_w}{T_w} + b\right)^{-1}, \left(\frac{Kwh}{operation}\right) \tag{8}$$

where T_w - the working duration of an operation, K_w - the proportionality constant being, a and b specific constant.

Besides traditional performance indicators, new indicators of [2] were defined, which take account of economic issues, environmental impacts or have synthetic character:

- Earning power [4]

$$EP_{ijk} = \frac{P_{ijk} - c_{ijk}(p_{ijk})}{A_{ijk} - t_{ijk}(p_{ijk})}, \left(\frac{Euro}{Euro\cdot\min}\right) \tag{9}$$

where means P_{ijk} - the price [euros], $c_{ijk}(p_{ijk})$ - expenses corresponding, p_{ijk} and which depend on parameters vector [euros], A_{ijk} - the asset of that workstation which performs [euros], $t_{ijk}(p_{ijk})$ - the time for processing the batch of samples when the workstation performs [minute], for operation k that belongs to job j of order i.

- Profit rate

$$PR = \frac{P_s - C_s}{\left(1 + k + \frac{\tau_{sr}}{T}\right)\cdot\frac{1}{v\cdot s\cdot t}}, \left(\frac{Euro}{\min}\right) \tag{10}$$

where P_s - the ratio P/V (the specific price), C_s - the ratio C/V (the specific cost), τ_{sr} - the time for worn tool changing (min).

- Investments efficiency

$$IE = \frac{P_s - C_s}{\sum_{i=1}^{n} Q_i}, \left(\frac{Euro}{Euro}\right) \tag{11}$$

where Q_i - means the value of the ith asset, from the n needed to run the considered process.

- Sustainable profit

$$SP = \frac{P_s - C_s}{\sum_{i=1}^{n}\left(\frac{CE_i}{T_i}\right)\left[1 + k + \frac{\tau_{sr}}{T}\right]\frac{1}{vst} + \frac{CE_{tool}}{vstT} + EC_s + CES + CE_{smater}}, \text{(Euro/Kg CO2)} \tag{12}$$

where CE_i - the carbon emission involved by the existence (the manufacturing/building), CE_{tool} - the carbon emission when manufacturing the currently used cutting tool, EC_s - means the specific energy consumption of the machining process, CES - the carbon emission signature (Kg CO_2/KWh), CE_{smater} - meaning the specific carbon emission during the machined material elaboration.

IV. Research Related to Optimization of Manufacturing Process Planning

Process planning describes the transformation of raw materials into products through planning the operations of a product based on machining features, the identification of manufacturing resources that are available to the operations and the determination of the machining sequence [5].

In existing research were taken into consideration objectives such as: the energy consumption, the manufacturing costs, the productivity, the manufactured surface roughness, the metal removing rate MRR, the cutting force magnitude.

For example, if the objective function is *the energy consumption,* in paper [6] it was made a cutting parameters optimization when turning AISI 1018 steel at constant material removal rate, using robust design. Rentsch *et al*. [7] present optimal manufacturing chain design and process operation, based on the discrete events modeling approach, empirically parameterized process models for heating, hot-rolling, forging and turning are combined to two alternative manufacturing chains for the manufacture of countershafts. Ma et al [8] focuses on the energy aspects in metal cutting and attempts to provide an overall assessment of energy consumption and energy efficiency against the operating conditions. Specifically, the effects of tool geometry and cutting parameters in turning of ANSI 4140 steel are investigated.

When the objective function is *the manufacturing cost,* Costa *et al*. [9] present minimizing the production cost associated with multi-pass turning problems. In [10] were determined optimal parameters of machining (cutting speed and feed) for getting minimal cost if turning process.

If the objective function is *the productivity,* Usubamatov [11] formulated a mathematical model for the optimization of multi-tool cutting processes on machine tools. Das *et al.* present in their paper [12] an optimization method of the cutting regime aiming to maximize the *metal removing rate MRR* in dry turning of AISI D2 steel.

If the objective function is *the manufactured surface roughness*, in [13] was determined the optimum machining parameters in surface grinding process operation on EN24 steel. Zerti *et al.* [14] determined optimal cutting parameters for machining by dry turning AISI D3 steel using mixed ceramic inserts under dry cutting conditions.

If the objective function is the *cutting force magnitude*, in [15] is presented an experimental study of main cutting force in turning of AISI 1040 steel and developed a model of the main cutting force during turning.

Besides the presented approaches, which are uni-criteria optimizations, other researchers performed multi-criteria optimizations. Winter [16] proposes a stepwise approach to compare alternative enabling factors in conjunction with the process parameters in order to reduce the costs and environmental impacts of a grinding process under consideration of technological requirements. In [17] the optimization strategy is to simultaneously minimize production time and cost and maximize profit rate meanwhile subject to satisfying the constraints on the machine power, cutting force, machining speed, feed rate, and surface roughness. Kübler [18] presented resource efficiency optimization of manufacturing processes for a turning process with respect to resource consumption, machining time and machining cost under product quality constrains and machine performance limits. Iqbal *et al*. [19] presents an experimental investigation for trade-off among energy consumption, tool life, and productivity of a metal cutting (machining) process. A total of 54 grooving experiments are performed under various predetermined combinations of the workpiece material hardness, cutting speed, cutting feed, and width of cut.

Regarding the optimization methods for finding the optimal solutions, the most used are: GA, PSO technique, Simulated Annealing (SA), ANN, fuzzy logic, Response Surface Methodology (RSM).

In [7] was used *GA* in combination with a fitness function to find the manufacturing chain design and process parameter set with the lowest energy and resource consumption for the effective manufacture of shafts. Petkovic describes in [10] the optimization of machining processes also by using *GA*, they were determined optimal parameters of machining, and were achieved minimal cost for the turning process. Hazza *et al.* has applied in [20] a multi objective *genetic algorithm* (MOGA) to solve the problem of optimization to minimize a power consumption cost. The constraints considered in this research are cutting speed, feed rate, depth of cut and rake angle.

The paper [9] is presents an algorithm hybrid *PSO* for minimizing the production cost associated with multi-pass turning problems. The proposed optimization technique consists of a PSO-based framework wherein a properly embedded SA, namely an SA-based local search, aims both to enhance the PSO search mechanism and to move the PSO away from being closed within local optima. In [21] is used *PSO* technique for finding the optimum set of values of input variables and the results are compared with those obtained by GA optimization in the literature.

Wang [22] uses feed-forward A*NN* using manufacturer's fuzzy preferences to determine the optimum cutting parameters by solving the multi-objective problem with the help of a neural network model. The objectives considered were productivity, operation cost, and cutting quality.

The paper [19] presents an experimental investigation and an application of *fuzzy* modeling for trade-off among energy consumption, tool life, and productivity of a metal cutting (machining) process. A fuzzy rule-based system is developed that consists of two modules: optimization and prediction. The former suggests the most suitable settings for the cutting parameters that would lead to accomplishment of various combinations of the objectives related to energy consumption, tool life, and machining productivity. The prediction module works out the predicted values of all the responses based on final values of the four input parameters.

Janardhan has applied in [13] *RSM* to determine the optimum machining parameters leading to minimum surface roughness and maximum metal removal rate in Surface grinding process. Bhuiyan and Ahmed shows in [15] the use *RSM* for experimental study of main cutting force in turning, well as GA for optimization of machining parameters to keep the main cutting force to a minimum.

V. Research Related to Optimization of Manufacturing Process Scheduling

Scheduling is the process of arranging and controlling labor and workloads in production / manufacturing process. Scheduling is used to implement the production planning based on the designed chain. This means that the material resources, human resources and equipments are selected in order to produce the planned quantity, on-time with minimum costs. All kinds of resources must be assured before start of production.

In manufacturing, scheduling purpose is to minimize production time and costs by facilitating production to cope with both the staff and the equipment.

During the last years, a large number of researchers analyzed the problems related to optimization of manufacturing process scheduling, regarding optimization criterion such as: energy consumption, the cost of manufacturing, the total earliness and tardiness time.

For example, if the optimization criterion is the *energy consumption*, paper [23] proposes a mathematical model to minimize energy consumption costs for single machine production scheduling during production processes. Tang et al. presents in [24] an approach to address the dynamic scheduling problem reducing energy consumption and makespan for a flexible flow shop scheduling. In [25] authors explicitly introduce the objective of minimizing energy consumption into a typical production scheduling model, i.e., the job shop scheduling problem, based on a machine speed scaling framework. He et al. proposes in [26] an energy-saving optimization method that considers machine tool selection and operation sequence for flexible job shops. The former seeks to reduce the energy consumption for machining operations, and the latter aims to reduce the idle energy consumption of machine tools. A mathematical model is formulated using mixed integer programming and the energy consumption objective is combined with a classical objective, the makespan. The proposed method is evaluated in a test case by two scenarios with different energy optimization schemes as well as the classical makespan objective. The results show that the proposed method is effective at realizing energy-savings.

If the optimization criterion is the *manufacturing cost*, in [27] the primary objective is to find the optimal sequence of jobs and the optimal resource allocation separately. The authors propose two separate models: minimizing a cost function of makespan, total completion time, total absolute differences in completion times and total resource cost; minimizing a cost function of makespan, total waiting time, total absolute differences in waiting times and total resource cost. Uruk et al. describe in [28] the study the problem of scheduling n identical jobs each of which has three operations to be performed on two machines placed in series. One of the operations can only be performed on the first, the other one by the second machine. The overall problem is to determine the assignment of the flexible operations to the machines and processing times for each operation, to minimize the total manufacturing cost and makespan simultaneously.

If the optimization criterion is *the total earliness and tardiness time*, in paper [29] authors address an unrelated parallel machine scheduling problem for jobs with distinct due dates and dedicated machines. The objective is to dynamically allocate jobs to unrelated parallel machines in order to minimize the total earliness and tardiness time.

The optimization problem to manufacturing process scheduling has been addressed through various optimization techniques: GA, PSO technique, SA, ANN.

In [30] was introduced a method based on the *GA* to address the dynamic rescheduling problem in flexible manufacturing systems (FMS). Yan introduced in [31] *GA* to optimize makespan and total energy consumption simultaneously at shop floor level. Moon et al. suggest in [32] a hybrid *GA* with blank job insertion algorithm and demonstrate its performance in simulation experiments.

Tang et al. to adopt in [24] a novel algorithm based on an improved *PSO* to search for the Pareto optimal solution in dynamic flexible flow shop scheduling problems.

Wang *et al.* used in [33] *ANN* for establishing the complex nonlinear relationships between the key process parameters and measured datasets of energy consumption and surface quality, they applied and benchmarked several intelligent algorithms, including pattern search, genetic algorithm and *SA*, to identify optimal solutions.

Numerous studies present a more complex approach regarding the *integrated process planning and scheduling* (IPPS), in [34] the authors say that integration of the two is essential to improve the flexibility of scheduling and achieve a global improvement for the performance of a manufacturing system. In order to facilitate the optimization of process planning and scheduling simultaneously, a mathematical model for the IPPS is established. Kumar proposes in [35] a framework for IPPS in a job shop environment for axis-symmetric components. Dai et al. present in [36] an energy-aware mathematical model for job shops that IPPS. With performance indicators such as energy consumption and scheduling makespan is established to describe a multi-objective optimization problem. Aqel et al. [37] present an optimization algorithm for IPPS problems, based on sorting the operations into different priorities.

In [36] the authors adopted a modified *GA* to explore the optimal solution (Pareto solution) between energy consumption and makespan. Finally, case studies of energy-aware IPPS are performed, and the proposed algorithm is compared with other methods. Lee proposes [38] a new approach to the IPPS using simulation *GA* in order to improve the solution quality until the scheduling objectives are satisfied. In [39] the authors present an *ant colony optimization* (ACO) algorithm in an agent-based system to IPPS, with the objective of minimizing makespan.

VI. Conclusion and Future Research Directions

After browsing a large volume of papers published in field of optimal manufacturing processes (not all included here, for reasons of space) one can draw the following conclusions:

- The *proposed* approaches are extremely diverse and in the same time each has particular characteristics due to the kind of studied problem and the scope of the optimization.
- In order to solve the optimization problems are used classical approaches of the existing methods, different combinations between these methods and some new and original developments of the existing methods.
- In most of the analyzed studies/cases the approach of the planning is separate from the approach of the scheduling.
- The most suitable approach of the optimization for the *manufacturing* activities seems to be integrated process planning and scheduling (IPPS).
- It is *required* an update of the performance indicators of manufacturing process and of objective functions used in optimization, which must have a synthetic character and reflect as well the interest of the manufacturers.
- *Optimization* should be multi-criteria or to be performed separately for many objective functions, in order to create an efficient Decision Support System (DSS) for

the manager of the manufacturing activities.

- Generally, the optimization of the manufacturing activities doesn't have a flexible character, taking into account the conditions from a given moment, without considering the perturbations which may appear or other influences.
- Energy efficiency and environmental impact of the manufacturing *processes* must be considered at least as restriction, if they are not considered even as objective function, according to the actual legal requirements.

In future research, a holistic methodology to approach manufacturing processes optimization will be proposed. The word holistic refers to both criteria of optimization and moment of applying the optimization in manufacturing processes. This approach is supposed to enable an improvement of the flexibility character.

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