UNIVERSITY OF MISKOLC Faculty of Mechanical Engineering		Institute of Information Science Department of Information Engineering

SOLVING SOME OPTIMIZATION PROBLEMS OF COMPUTER AIDED PROCESS PLANNING IN CIM-ENVIRONMENT

Summary of

Ph.D. Thesis

by

Samad Dadvandipour, **MSc**

Mechanical Engineer

Scientific Advisor: Prof. Tibor Tóth, **DSc**

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1. Introduction

Computer Integrated Manufacturing (CIM) provides a complete automation of manufacturing companies, with all processes working under computer control systems linking them together. It includes Computer Aided Design (CAD), Computer Aided Manufacturing (CAM), Computer Aided Process Planning (CAPP), Computer Numerical Control of machine tools (CNC), Direct (Distributed) Numerical Control of machine tools (DNC), Flexible Manufacturing Systems (FMSs), Automated Storage and Retrieval Systems (ASRS), Automated Guided Vehicles (AGVs), the use of robotics and automated conveyance, Computerized Scheduling and Production Control and a business system integrated by a common database. CAD/CAM is very essential to reducing cycle times in an organization. Computer Aided Process Planning (CAPP) emerges as a key factor in CAD/CAM integration because it is the link between CAD and CAM. CAD techniques make use of Group Technology (GT) to create similar geometries for quick retrieval electronic files replacing drawing rooms. CAD/CAM integrated system provides design and drafting, planning and scheduling, and fabrication capabilities. CAD provides the electronic part images, and CAM provides the facility for tool path cutters to take on the workpiece. Advanced software programs can analyse and test designs before a prototype is made. Finite element analysis programs allow engineers to predict stress points on a part, and the effects of loading. Generative, variant and vario-generative process planning are advanced CAPP methods in integration of CAD/CAM.

This Thesis is about solving some *optimization problems of Computer Aided Process Planning (CAPP) in CIM environment concerning machining processes*. In this respect optimum determination of cutting parameters (depth of cut, feed rate and cutting speed) is of a great importance especially for NC/CNC machine tools. Increasing the intensity of these parameters may result in decreasing the machining time of the given operation, but at the same time, it increases the tool cost as a consequence of loading and wearing of the tool, which is not economical and cost effective. Then we can realise the fact that there will be contrasted effects if we do not select appropriate cutting parameters. In order to find a reasonable compromise it is necessary to solve optimization problems. This part of the Thesis aims at *optimization of tool life* using appropriate cutting parameters. This trial results in decreasing of the feed rate and the spindle speed along with arranging the surfaces of the workpiece to be machined in accordance with decreasing machining times. It is resulting in increasing of the tool life. Solution of this optimization problem needs determination of machining time, spindle speed, determination of weighted average tool life taking into consideration the local tool lives for number of cuts and database using computer program. *Determination of the optimum rate of stock removal factor* is another optimization problem related to this Thesis. Determination of optimum stock removal factor in machining processes is very important, because the intensive parameter values (depth of cut, feed rate and cutting speed) are originating from its rate. The resultant output (the optimum rate of stock removal factor) comes from a new idea which suggests that *the total cost of the operation* for the machining processes to be an *objective function* and *the limit of total machining time* proposed by the dispatcher to be *the constraint* for the solution of this optimization problem. Using the total cost of operation as an objective function and the limit of total machining time give the chance to the up-to date companies that try to increase their productivity, to face rapidly changing market conditions, to improve product design, and to increase product quality for better customer satisfaction in time. To solve the problem a mathematical model based on *Lagrange multiplier* method has been applied. The derivation of the mathematical model results in *a new optimum rate of stock removal factor*, which its rate is the same for all the layers in question. For example in case of turning processes it is clear that the smaller the turning diameter the greater the cutting speed but as the rate of the stock removal factor for the solution of this optimization problem is the same for the all the layers, then in this case the depth cut and feed rate should be decreased. This is an advanced solution for optimization of cutting processes. *Optimization of the total cost of the operation* is very fundamental and significant problem in machining processes. This covers another important part of this Thesis. The new idea works based on the variable rate of stock removal factors. The outputs realising these factors employs *the total cost of the operation* as an *objective function* and *the maximum weighted average tool life allowed to be utilized* as *the constraint*. To solve this problem a mathematical model also based on *Lagrange multiplier* method has been developed. The derivation of the mathematical model results in *highly non-linear system of equations*, which we have to solve for rate of stock removal factors and the range of Lagrange multiplier. Converting the highly non-linear system of equations needs application of a special matrix so called Hasse matrix. Using Hasse matrix a linear system of

equations can obtain for the solution of the rate of stock removal factors for each chain and Lagrange multiplier as well (constant). Substituting the obtained results in the objective function is the solution of this optimisation problem. A computer program and numerical method have been used for solution of these optimization problems.

2. Preliminaries

In most cases of production planning and scheduling the required production time for any specific task is known in advance. However, in practice, it is possible to vary production speed by altering the manufacturing conditions. An important example of this is metal cutting manufacturing processes. Research on *optimum cutting parameters* goes back to 1907 *(Taylor, F. W.).* Since then, this problem has been approached using different methods. Different optimization methods, ranging from simple classical methods to sophisticated constrained optimization techniques considering the probabilistic nature of problem and geometric programming has been reported to be successful. Analysis of single and multi-pass turning under practical constraints has been done using minimum production cost or time criteria. Since the results obtained by using these two different criteria are always different, *Okushima* and *Hitomi*, *Wu* and *Ermer*, *Boothroyd* and *Russek* have used a maximum profit rate, which yields a compromise results, in subsequent investigations. However, in practice profit rate is not a steady variable, therefore this criteria does not always produce realistic results. Some methods reported in the literature to solve optimization problems for machining conditions include performance envelope, linear programming, Lagrange multipliers, geometric programming, dynamic programming, graphical methods and artificial intelligence. *Walwekar* and *Lambert*, *Ermer* and *Petropoulos* stated that geometric programming method is more powerful than other optimization methods in determining the optimum machining conditions when the solution is restricted by one or two inequality constraints. But they also pointed out that as the number of constraints increases another optimization methods should be employed together with the geometric programming. Cutting rate-tool life function theory studied by *Ravignani*, *Tipnis* and *Friedmann* has permitted determination of machining economic optima for machine tools by means of two variables: the metal removal rate and the tool life. Application of this research to a machine tool is limited by cutting constraints, which depend on machine tool and workpiece characteristics. Yet tool life may be submitted to large variations caused by workpiece heterogeneity. These variations may be a disadvantage in batch production when tool life change is determined *off-line* to optimize cost production. *Richard, J., et al.* have studied an adaptive control system for CNC machine. In their approach tool wear is measured during machining and the system maintains tool life constant by means of cutting speed (v) variations, thus the cost function is optimized *on - line* in the constraints domain. The principal advantages are control of machining time for batch production and the maintaining of constant production costs which improve production planning. A simple method to understand and apply to the optimization problem was published and explained by *Kiliç*. This method is particularly applicable to situations where the available machine speeds and feeds are stepped. It searches the optimum point along the constrained border, reaching the optimum in a number of steps equal to the sum of the number of available feeds and spindle speeds. Objective function has only two variables (feed rate and cutting speed) but it is not possible to explicitly express one of the variables in terms of the other. *Kiliç* and *Çogun,* developed a graphical model in order to draw the constant value of the objective function and determine the optimum point. It was developed for single pass applications. Since multi-pass operations for economic reasons, recent efforts have made to determine optimal machining conditions for multi-pass operations. *Iwata, et al,* applied dynamic programming for multi-pass turning operations. This method does not require equal depths of cuts for passes. *Hinduja, et al.* defined the objective function and constraints in terms of depth of cut and feed rate and evaluated finish pass and rough passes separately. The summation of the depth of cut of the rough passes is not always equal to the total depth of cut and the methods introduced to equalize these values may not always give the optimum solution. They suggested using the maximum allowable depth of cut of the tool for the finish pass, which is also open to discussion. In the work of *Cakir, M. C.* and *Gurarda, A.,* total depth of material to be removed including finish pass and rough passes are cut with the same tool. This volume is divided into sections and each section is threatened as a single pass operation by taking the constraints maximum and minimum feed rate and speeds available, cutting power, tool life, deflection of work piece, axial pre-load and surface roughness into consideration. In this work optimum values of machining parameters were found by using a search method in the feasible region, which calculates the minimum cost value and corresponding optimum feed rate and cutting speed values. After applying this method to each possible section and storing them in a matrix form, dynamic programming techniques were applied to minimize the objective function *Boothroyd* and *Rusek* used a maximization criterion for the rate of profit. *Philipson* and *Ravindran* employed different single-objective as well as bi-criteria mathematical models. *White, Lee* and *Kwak* used computer simulation. *Hati* and *Rao* considered three objectives: machining cost, production rate, and profit rate. *Ghiassi, et al.* used a multiple-objective linear programming technique. *Tabucanon* and *Mukyangkoon* presented interactive goal programming. *Malakooti* and *Deviprasad* used an interactive multiple-criteria approach for parameter selection in metal cutting. Their objectives were to minimize cost per part, machining time per part, and roughness of the work surface, simultaneously. They utilized a gradient-based multiple-criteria decision-making heuristic approach for selecting optimal parameters in metal cutting. *White* and *Houshyar* presented single-variable optimization techniques in which cutting speed was the variable under consideration. A single-stage machining model was developed that deals with machining times and cost as functions of speed. Different elements of time and cost were introduced and their relation to cutting speed were determined. The main contribution of their work was to add the cost of “quality” to the objective function, thus modifying existing models to explicitly recognize how roughness of the part will affect its machining cost. This modification is applicable to those cases where a marginal improvement in the quality of the part may result in the elimination of a secondary process or the use of a different, more costly process. *Somló, J.* used a method, which made possible to enforce the management goals when choosing the cutting parameters. It is possible to solve this problem by the development of the so-called secondary optimization method. The secondary optimization connects the cutting data with the management requirement. The application of this is not trivial because it needs at every new management situation a new technological processing. It is possible to realize the secondary optimization when the machine tool is equipped with adaptive control unit. For this, a new override method was proposed which can also be used in systems without feedback from the cutting process (without AC in the classical sense) using properly suited CNC devices. A new optimization method based upon intensity type compact variables developed by *Tóth, Tibor, Detzky, Ivan* and *Rayegani, Farzad*. The proposed mathematical model is of *three* components they are as follows:

(1) Constraints system;

(2) Objective function;

(3) Tool life equation.

The *independent variables (constraint system)* of the model are the parameters and their values are to be optimized (e.g. for *turning*: depth of cut (*d*), feed rate (*f*) and cutting speed (*v*); for *grinding* with longitudinal feed: depth of cut (*d*), longitudinal feed (*f*) and the revolution number of workpiece (n_w)). The *objective function* may be defined as minimum cost or maximum productivity for the given operation element according to the user's wish and the *tool life (T) equation* is additionally used as the third component of the new model. At this model it is supposed that a proper solution for the model exists and it is a closed set (e.g. variables *(d), (f), (v)* have finite values only).

3. Objective of Thesis

In producing the goods manufactured by the engineering industries, ideas originating from *management* and the different departments responsible for preparatory activities and actions of production (e.g. design, production planning, production engineering etc.) need to be communicated to those working on the '*shop floor*'. Computer Aided Design (CAD) and Computer Aided Manufacturing (CAM) and the link which integrates them namely Computer Aided Process Planning (CAPP) are the key points in improving productivity to allow manufacturing enterprises to maintain a competitive edge, as there will no a guarantee for any company or nation to be sure of having a dominant position in a specific market if the importance of CAD, CAM and CAPP is not over stressed in CIM environment.

In order to carry out the entire process to be accomplished in as economical manner as possible, *cost accounting* and *time* have to be brought into the picture and information from these groups is used as a key in design and manufacturing decisions. These *two entities* constitute the main starting point of the Thesis, as without considering them it is quite impossible to accomplish the entire process in *economical manner*, furthermore any economical aspects need *optimization procedures*. The optimization procedures in this Thesis are based on *optimum determination of the values of technological parameters*, *optimum determination of the rate of stock removal factor* and *optimization of the total cost of given operation*. In this respect, as a result of the justification of CIM system, significant relationships between *technical* and *managerial data* can be established.

4. The fundamentals used in the research

As is known, the practical application of scientific works can be approached in two ways from theoretical point of view:

1. On the base of their most important characteristics, we group the problems and allocate the applicable methods to the problems (problem-oriented aspect);

2. We arrange the methods in accordance with the tools of solutions and we allocate the problems to the suitable methods (methodological aspect).

In my Thesis I have used both the two approaches and their combination as well. As general methods belonging to the problem-oriented aspect I utilized the following:

- **the analysis oriented to recognizing and knowing the problem;**
- **the synthesis targeted to solving the problem;**
- **the optimisation suitable for solving the best solutions determined by the given constraint and the valid laws;**
- **technical heuristics and modelling and formalization.**

As examples to the methodological aspect, the use of *Lagrange multiplier*, and *numerical Newton* methods and *computer programming* can be mentioned to special problems as problem oriented aspect.

5. The new scientific results – THESIS

There have been a lot of efforts concerning optimization of cutting conditions. In this respect we may say that technological parameters have the best roles, as they control the economical aspects. From this point of view the economical aspects in optimization of cutting conditions may be marginal cost, machining time, tool life and productivity. For example increasing the feed rate, the cutting speed or depth of cut, may increase the productivity and decrease the machining time, but at the same time it decreases the tool life due to tool wear and increase the machining cost.

Tóth, Tibor has drafted the basic principles for determination of cutting conditions. In 1988 *Tóth, Tibor* and *Detzky, Ivan* published the theoretical fundamentals of the new optimization method based on rate of stock intensity factor Q (cm^3/min), as well as the specific cost equivalent time function $t\ (Q, R)$ (min/cm^3) as an objective function. A new parameter R (cm^3/min) depends on the characteristics of the given tool and feed rate as well.

Furthermore in his book published in 1998, *Tóth, Tibor* gave a complete mathematical model with the most important constraints and the solving method as well.

Utilizing the above-mentioned fundamentals and principles for determination of cutting conditions the author has further developed mathematical models and computer programs for solution of the following three Thesis:

1. Tool life synchronization in case of a prescribed average tool life (**Thesis 1**).
2. Secondary optimization with the additional constraint related to the limit of total machining time of the workpiece (**Thesis 2**).
3. Secondary optimization with the additional constraint related to the average tool life calculated on the base of local tool lives and local machining times (**Thesis 3**).

THESIS 1

In many machining operations it may prove advantageous to restrict the feed rate and spindle speed within certain limits. In this respect we may say that technological parameters have the best roles, as they control the economical aspects.

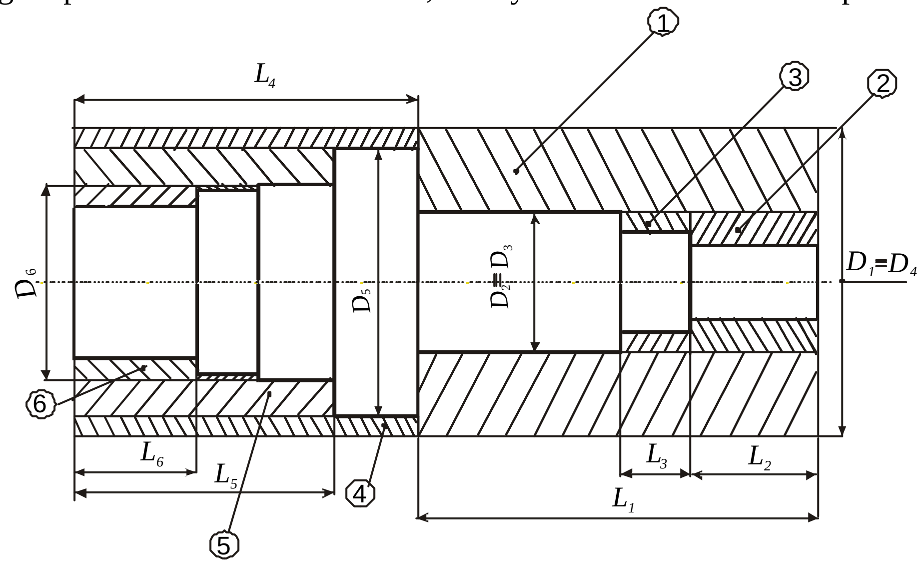

Fig.1. An example of workpiece to be cut

The optimum determination of cutting parameters depth of cut *(d_i)*, feed rate, *(f_i)* and cutting speed *(v_i)* is of a great importance especially for NC/CNC machine tools. Increasing the intensity of these parameters may result in decreasing the machining time of the given operation, but at the same time, it increases the tool cost as a consequence of loading and wearing of the tool, which is not economical and cost effective. Then we can realize the fact that there will be contrasted effects if we do not select appropriate cutting parameters. In order to find a reasonable compromise it is necessary to solve optimization problems. This part of the Thesis aims at *optimization of tool life* using appropriate cutting parameters.

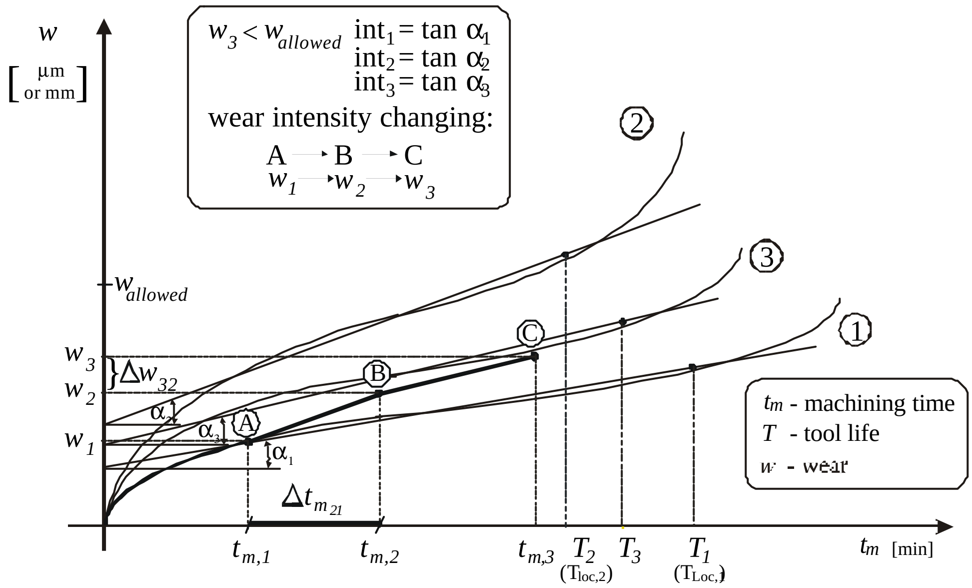

Fig.2. Relationships between machining time and tool wear

The results obtained from this trial are decrease in feed rate, decrease in spindle speed and arrangement of surfaces of workpiece to be machined in accordance with decreasing machining times, which in consequence is increasing the tool life. Solution of this optimization problem needs determination of machining time, determination of weighted average tool life taking into consideration the local tool lives for number of cuts, arranging the surfaces in accordance with decreasing machining times and database using computer program. Let us assume that a general rough turning process will be performed and dimension chain of a shaft (see: Fig.1.) has been given in accordance with the machining sequences (removal of stock): D_i , L_i, (i=1,2…z). In addition to this, the cutting parameters along with allowable tool life are known. The workpiece is machined without changing the tip edge. The explanation for the process is as follows (Fig.2.): The given tool edge is used under changeable cutting conditions. For the sake of simplicity we suppose that the edge is used according to the first $w = w(t_m)$ curve until the machining time $t_{m,1}$ (see curve 1, point A). From this point because of the higher cutting intensity we change the cutting conditions, then the tool wear will follow curve 2 (see phase A→ B, until the machining time $t_{m,2}$). At the machining time $t_{m,\ 2}$ we also change cutting conditions according to curve 3 until the machining time $t_{m,\ 3}$. Here the wear intensity are denoted by $int_1 = tan\alpha_1$, $int_2 = tan\alpha_2$ and $int_3 = tan\alpha_3$ where the smallest is $int_3 = tan\alpha_3$ in this theoretical relationships. Then our suggestion is to calculate a weighted average tool life T_w (min) with respect to each local tool life T_i (min) in accordance with its proportional weight. It means that if a layer removal is very time consuming, then the local tool life belonging to it will influence the average tool life proportionally to a greater extent in comparison with another layer removal of which needs smaller time.

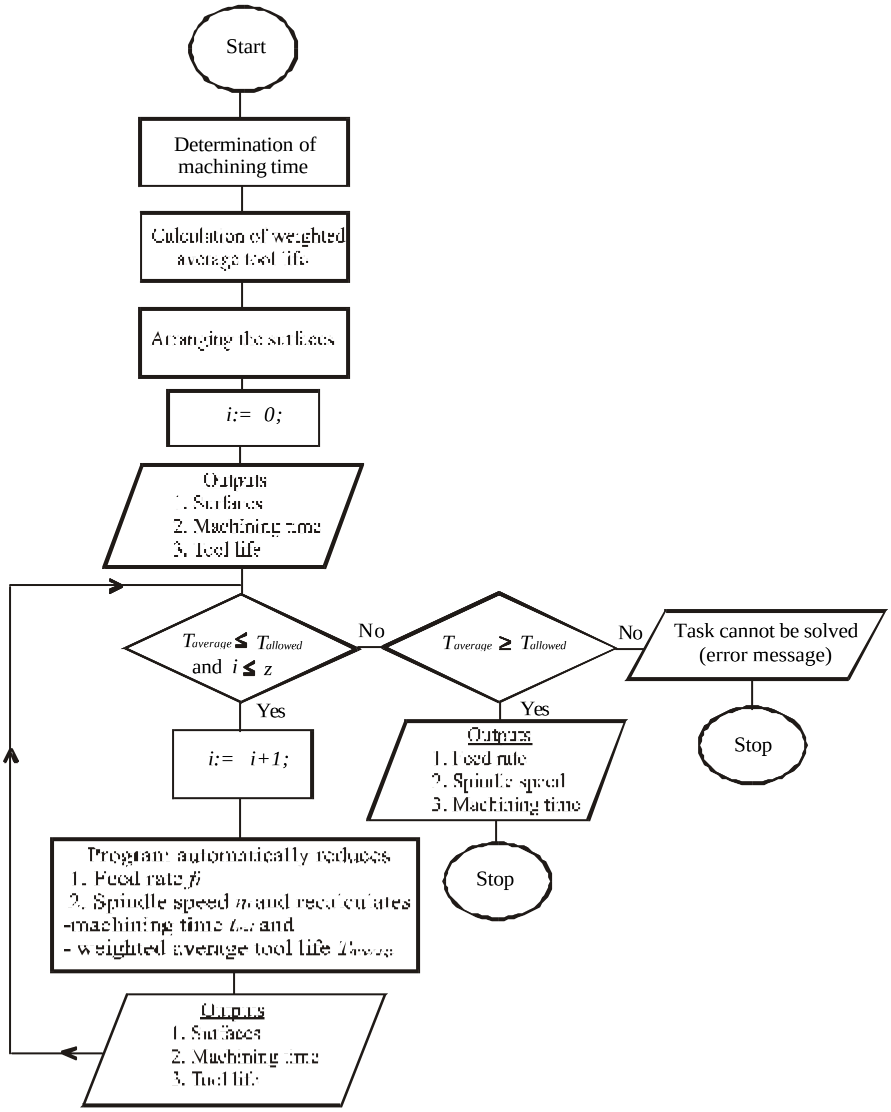

Fig.3. Elaboration of an algorithm for tool life synchronization

At the new method the tool optimization is a loop of reduction of feed rates and spindle speed taking into consideration the weighted average tool life as a constraint and arranging the surfaces in accordance with decreasing machining times.

For this purpose and demonstrating the practical use of the new method I have further developed a computer program (Fig.3.).

<u>Note:</u> In this algorithm i is number of steps (i.e. $i = 0$ or $i = i + 1$, so on) and z is number of chain elements.

THESIS 2

Based on principles and fundamentals of optimization problems I have further developed a mathematical model for <u>*determination of the optimum rate of stock removal factor*</u> Q_i (cm^3/min). It works out based on <u>*the total cost of the given operation*</u> K_S (HUF) as an <u>*objective function*</u>, taking into consideration <u>*the limit of*</u>

total machining time $\sum_{i=1}^{z} t_{m,i} = t_m \le t_{ml}$ (min) as a *constraint* valid for the operation as a whole. We assume that the dispatcher's time limit t_{ml} related to the total machining time t_m of operation in question is realizable. For example it is based on empiric considerations from the workshop. Determination of optimum stock removal factor in machining processes is very important, because the intensive parameter values (depth of cut, feed rate and cutting speed) are originating from its rate.

To solve the problem a mathematical model based on *Lagrange multiplier* method has been applied. This mathematical model takes into consideration the objective function along with the constraint. Derivation of the mathematical model results in *a new optimum rate of stock removal factor*, which its rate is the same for all the layers in question.

$$Q_1 = Q_2 = Q_3 = \ldots\ldots\ldots\ldots = Q_i = \frac{V_\Sigma}{t_{ml}}.$$

Where:

V_S: is the total volume to be removed.

For example in case of turning processes it is clear that the smaller the turning diameter the greater the cutting speed but as the rate of the stock removal factor for the solution of this optimization problem is the same for the all the layers, then in this case the depth of cut and feed rate should be decreased. This is an advanced solution for optimization of cutting processes.

In connection with the new result we have to consider the following discussion as well.

Discussion:

It is easy to see that there are three possible cases:

(1) If $t_m < t_{ml}$ then the local optimum parameter values can be regarded as global optimum ones for the operation in question.

(2) If $t_m = t_{ml}$ then the question has got only theoretical significance, because of real type calculation.

(3) **If $t_m > t_{ml}$ then we have to assume that the difference $Dt_m = t_m - t_{ml}$ is empirically well established and it can be performed. In this case the cost for limit of total machining time t_{ml} will be greater than the cost for the total machining time t_m calculated from the local optimisation. It is because of more intensive parameter values originating from new Q_i values.**

THESIS 3

Considering the optimization problem with regards to fundamentals and principles mentioned previously. I have further developed the mathematical model along with an advantageous numerical solving method of programming. The new method of optimization works based on *the variable rate of stock removal factors* Q_i (cm^3/min) and aims at *minimizing the total cost of the given operation* K_S (HUF) as *the objective function*. The *constraint* for this purpose is *the maximum weighted* *average tool life that is allowed to be utilized* $T_{w,allowed} \geq T_w$ (min). Where T_w (min) is the prescribed weighted average tool life in changing circumstances. To find a suitable solution for the new optimization problem, a mathematical model based on *Lagrange-multiplier* method has also been used.

1. Solving the mathematical model requires analysis of the function $y\,(Q_i, l\,)$, which is the combination of the objective function and its constraint. The gradient of this function results in a highly non-linear system of equations, which needs a multidimensional numerical method to solve it. The unknown parameters are rate of stock removal factors Q_i and Lagrange multiplier l .

2. Converting this highly non-linear system of equations needs application of a special matrix so called Hasse matrix. Using Hasse matrix a linear system of equations can obtain for the solution of the rate of stock removal factors for each chain and Lagrange multiplier l (constant) as well.

3. The developed program works on the base of numerical multidimensional *Newton* method (gradient method). This matrix is the second derivative of $y\,(Q_i, l\,)$.

4. The *process needs iteration step*s by computer program, which turns the gradient vector $y\,'(\,Q_i\,, l\,\,)$ to zero.

5. Substituting the obtained results Q_i and l in the objective function is the solution of this optimization problem.

Computer realization of these techniques needs special efforts as convergence needs special studies of the problems and experiments. The new method of optimisation solves multidimensional problems in cutting processes.

Characteristics and advantages of the new method

- The new method is capable to solve the multidimensional optimization problems in machining processes.
- A numerical solution based on Newton-method (gradient method) has been used to solve the highly non-linear system of equations for *N+1* unknowns namely the range of stock removal factors Q_i and Lagrange multiplier λ.
- Using Hesse matrix is an advanced solution to convert the highly non-linear system of equations into linear ones.
- As the new method of optimisation is equipped with computer program, then it makes it easy to calculate the range of stock

removal factors Q_i and Lagrange multiplier ? using iteration methods. Depending on the number of chains, lengths and number of cuts in a workpiece to be cut, the iteration does not stop till the gradient vector of the function $y(Q_i, l)$ does not turn to zero

- Modifying each step of iteration the unknown correction vector S_k has been used for the solution of the system of linear equations $H(X_k).S_k = -y'(X_k)$ where $H(X_k)$ Hesse matrix the second derivative of $y(Q_i, l)$ and $y'(X_k)$ the gradient of function $y(Q_i, l)$ are only numbers.
- Application of the computer program gives the chance to use technological parameters along with geometry data as input, which can further be stored and used in-group technology in CAPP system.
- **The method is a new and solves sophisticated highly non-linear system of equations of the mathematical model used for optimization problems in cutting conditions.**
- **The new method is restricted to turning operation, and can be generalized for other cutting processes as well.**

6. Applications of the new scientific results

Process Planning System is a very wide area in manufacturing system as it deals with how to manufacture an individual product, being an assembly or a single-part. It aims at manufacturing the considered product in the most cost effective way considering technological constraints and preferences. This area includes: interpretation of the product model, selection of machines, set-ups, tool designing as well as machining methods and machining sequences and NC/CNC programming. At this area there are some types of automated process planning (e.g. the variant method, and generative method which represent the available knowledge and experiences) this kind of automated process planning is called Computer Aided Process Planning (CAPP).

In order to apply CAPP in a cost effective way, and to over come the problems arising form the technical and economical aspects, companies usually try to reduce their costs, lead-time and at the meantime increase their

productivity. These objectives are not obtained without consideration of optimum use of machines, machine tools and other marginal costs.

Considering the optimization problems the new methods applied in this Thesis have resulted in developing of three new results which two of them equipped with two practical programs as well.

These three new results can solve some optimisation problems of Computer Aided Process Planning (CAPP) in CIM environment. We can use these new results in order to test whether the workpiece to be cut is cost effective or not. The application of the new method may be as follows:

1. **Using the new method we can test the new product plan, before any prototyping process, then the test results can give the chance whether the applied plan for the new product fulfils the decision makers' satisfaction or not.**

2. **As cost equivalent-time function gives the specific time of the rate of stock removal to the lowest cost, the new method can express technical and economical aspects at the same time.**

3. **The new method can solve and optimize the multidimensional cutting conditions problems by means of iterations and based on the geometry of the new product and given technological parameters, the most optimum values for the rate of stock removal factors and consequently for time-equivalent cost function are obtained.**

4. **Based on the new method lots of products plan with different geometry can be tested and stored for the further application or collected to be used in Group Technology (GT) as well.**

5. **The new method can also be used not only in industry but also in educational field as well, where there is no any access to CAD/CAM system.**

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