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SCOPE & TOPICS

Advances in Production Engineering & Management (APEM) is an interdisciplinary refereed academic journal. The main goal of the APEM is to present high quality research developments in all areas of production engineering and production management, as well as their applications in industry and services, to a broad audience of academics and practitioners. In order to bridge the gap between theory and practice, applications and case studies are particularly welcome. For theoretical papers, their originality and research contributions are the main factors in the evaluation process. Fields of interest include, but are not limited to:

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General approaches, formalisms, algorithms, or techniques should be illustrated with significant applications that demonstrate their applicability to real-world problems.

EDITORIAL

Welcome to the new issue of the *Advances in Production Engineering & Management* (APEM), ISSN 1854-6250. The mission of the APEM is to serve as a non-profit platform for publishing of scientific and professional articles and other useful resources (practical information, book reviews, equipment and software reviews etc.). Production engineering and production management are branches that concern the development, improvement, implementation and evaluation of integrated systems of people, knowledge, equipment, energy, material and process. They draw upon the principles and methods of engineering analysis and synthesis, as well as mathematical, physical and social sciences together with the principles and methods of engineering analysis and design to specify, predict and evaluate the results to be obtained from such systems. Whereas most engineering disciplines apply skills to very specific areas, production engineering & management can be applied in virtually every industry or in services.

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Editor-In-Chief

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PROCESS PARAMETERS MODELING AND OPTIMIZATION OF WIRE ELECTRIC DISCHARGE MACHINING

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Abstract:
Wire electrical discharge machining (WEDM) is a widely accepted non-traditional material removal process used to manufacture components with intricate shapes and profiles. Due to many parameters and the complex and stochastic nature of the process, achieving the optimal performance is a very difficult task. The objective of this present work is therefore to discover the relationship between the performance measures of the process and its controllable input parameters and subsequently to find the optimal combination of the input parameters to achieve the maximum process performance. A mathematical model using response surface modeling (RSM) approach is developed for correlating the inter-relationships of various wire electric discharge machining (WEDM) parameters with performance measures. A non-traditional optimization technique, known as particle swarm optimization (PSO), is then applied to find the optimal combination of process parameters with an objective to achieve maximum machining speed for a desired value of surface finish. It is observed that the results of optimization obtained by using PSO algorithm show significant improvement over those obtained using traditional optimization technique. Also the results obtained are in good agreement with those obtained through practical experimentation. The mathematical model developed in this work will help the practitioners to simulate the process performance on any WEDM machine. Moreover, the optimization using PSO algorithm will help EDM users to achieve significant improvement in process performance than by using traditional optimization algorithms and handbook recommendations.

Key Words: Wire electric discharge machining, Response surface modeling, Particle swarm optimization

1. INTRODUCTION

In recent years an increasing demand for machining of complex shapes made of hard and difficult-to-machine materials with exact tolerances and surface finish resulted in the development of many advanced machining processes based on chemical, electro-chemical, thermal, electro-thermal, mechanical and other means of material removal. Wire electric discharge machining (WEDM) is one of the widely accepted advanced machining processes used to machine components with intricate shapes and profiles. It is considered as a unique adaptation of the conventional EDM process which uses an electrode to initialize the sparking process. As shown in Figure 1, WEDM utilizes a continuously travelling wire electrode made of thin copper, brass or tungsten. On application of a proper voltage, discharge occurs between the wire electrode and the workpiece in the presence of a flood of deionized water of high insulation resistance. The material is eroded ahead of the wire through a series of repetitive sparks between electrodes, i.e. workpiece and the wire.

WEDM has been gaining wide acceptance in modern tooling applications, machining of advanced ceramic materials and modern composite materials due to the following reasons [1]:

- As the wire diameter is small (0.05–0.3 mm), the process is capable of achieving very small corner radii.
- The wire is kept in tension using a mechanical tensioning device reducing the tendency of producing inaccurate parts.
- During the WEDM process there is no direct contact between the workpiece and the wire, eliminating the mechanical stresses during machining.
- WEDM process is able to machine exotic and high strength and temperature resistive (HSTR) materials and eliminate the geometrical changes occurring in the machining of heat-treated steels.

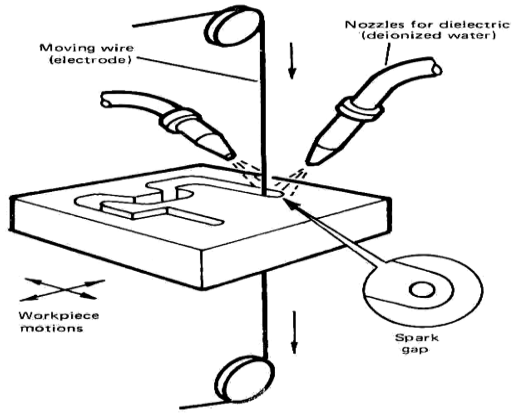

Figure 1: Basic sheme of wire EDM process.

Wire EDM manufacturers and users always want to achieve higher machining productivity with a desired accuracy and surface finish. Performance of the WEDM process, however, is affected by many factors such as servo feed setting, peak current, pulse on time, pulse off time, wire tension, etc. and a single parameter change will influence the process in a complex way. Because of many parameters and the complex and stochastic nature of the process, achieving the optimal performance, even for a highly skilled operator with a state-of-the-art wire EDM machine is rarely possible. An effective way to solve this problem is to discover the relationship between the performance of the process and its controllable input parameters by modeling the process through suitable mathematical techniques and optimization using suitable optimization algorithm. In the present work response surface methodology is used to model the process whereas the optimum parameter setting is achieved through an advanced optimization algorithm known as particle swarm optimization (PSO) algorithm.

The next section presents a brief review of the past research work done on the modeling and optimization of wire electric discharge machining process parameters.

2. REVIEW OF PAST RESEARCH WORK

Scott et al. [2] used a factorial design requiring a number of experiments to determine the most favourable combination of the WEDM parameter. They found that the discharge current, pulse duration and pulse frequency are the significant control factors affecting the material removal rate (MRR) and surface finish, while the wire speed, wire tension and dielectric flow rate have the least effect. Tarang et al. [3] employed a neural network system with the application of a simulated annealing algorithm for solving the multi-response optimization problem. It was found that the machining parameters such as the pulse on/off duration, peak current, open circuit voltage, servo reference voltage, electrical capacitance and table speed are the critical parameters for the estimation of the cutting rate and surface finish.

Anand [4] used a fractional factorial experiment with an orthogonal array layout to obtain the most desirable process specification for improving the WEDM dimensional accuracy and surface roughness. Liao et al. [5] proposed an approach of determining the parameter settings based on the Taguchi quality design method and the analysis of variance. The results showed that the material removal rate and surface finish are easily influenced by the table feed rate and pulse on-time, which can also be used to control the discharging frequency for the prevention of wire breakage. Spedding and Wang [6] optimized the process parameter settings by using artificial neural network modeling to characterize the WEDM workpiece surfaces. Konda et al. [7] classified the various potential factors affecting the WEDM performance measures into five major categories namely the different properties of the workpiece material and dielectric fluid, machine characteristics, adjustable machining parameters, and component geometry. In addition, they applied the design of experiments (DOE) technique to study and optimize the possible effects of parameters during process design and development.

Gokler and Ozanozgu [8] studied the selection of the most suitable cutting and offset parameter combination to get a desired surface roughness for a constant wire speed and dielectric flushing pressure. Huang and Liao [9] presented the use of Grey relational and S/N ratio analyses to demonstrate the influence of table feed and pulse on-time on the material removal rate. Tosun et al. [10] investigated the effect of the pulse duration, open circuit voltage, wire speed and dielectric flushing pressure on the workpiece surface roughness. It was found that the increasing pulse duration, open circuit voltage and wire speed increases with the surface roughness, whereas the increasing dielectric fluid pressure decreases the surface roughness.

Tosun et al. [11] presented an investigation on the optimization and the effect of machining parameters on the kerf and the MRR in WEDM operations. The simulated annealing algorithm was then applied to select optimal values of machining parameters for multi-objective problem considering minimization of kerf and maximization of MRR. Hewidy et al. [12] developed a mathematical models based on response surface methodology for correlating the inter-relationships of various WEDM machining parameters of Inconel 601 material such as peak current, duty factor, wire tension and water pressure on the metal removal rate, wear ratio and surface roughness. Kuriakose and Shunmugam [13] presented a multiple regression model to represent relationship between input parameters and two conflicting objectives i.e. cutting velocity and surface finish. A multi-objective optimization method based on a Non-Dominated Sorting Genetic Algorithm (NSGA) is then used to optimize Wire-EDM process.

Sarkar et al. [14] presented an approach to select the optimum cutting condition with an appropriate wire offset setting in order to get the desired surface finish and dimensional accuracy for machining of γ-titanium aluminide alloy. The process has been modeled using additive model in order to predict the response parameters i.e. cutting speed, surface finish and dimensional deviation as function of different control parameters such as pulse on time, pulse off time, peak current, servo reference voltage, wire tension and dielectric flow rate. Kanlayasiri and Boonmung [15] developed a mathematical model using multiple regression method to formulate the pulse-on time and pulse-peak current to the surface roughness.

Although various researchers have considered the effect of different process parameters on various performance measures, these efforts needs to be further extended by considering more performance measures and more input parameters. Machining speed and surface finish are considered to be very crucial and important performance measures for WEDM, hence the same are considered in the present work. A mathematical model relating these performance measures with four important process parameters namely, pulse on time (T_{on}), pulse off time (T_{off}), peak current (I_p) and servo feed setting (F), is developed using a second order response surface modeling technique, as first-order models often give lack-of-fit [16]. Furthermore, it is revealed from the literature that mathematical programming techniques like method of feasible direction, Taguchi methods etc. had been used to solve optimization problems in wire electric discharge machining process. However, these traditional methods of optimization do not fare well over a broad spectrum of problem domains. Moreover, traditional techniques may not be robust and they also tend to obtain a local optimal solution. Considering the drawbacks of traditional optimization techniques, attempts are being made to optimize the machining problem using evolutionary optimization techniques. These methods use the fitness information instead of the functional derivatives making them more robust and effective. These methods thus avoid the problem of getting trapped in local optima and enable to obtain a global (or nearly global) optimum solution. Efforts are continuing to use more recent optimization algorithms, which are more powerful, robust and able to provide accurate solution. Particle swarm optimization developed by Kennedy and Eberhart [17] is one of the recent algorithms and reported to be the better algorithm for continuous optimization as well as discrete optimization problems [18]. Hence, the same is considered in the present work.

The next section describes the development of a mathematical model for wire electric discharge machining process.

3. RESPONSE SURFACE MODELING (RSM)

Response surface modeling (RSM) is a collection of statistical and mathematical methods that are useful for the modeling and optimization of the engineering science problems. RSM quantifies the relationship between the controllable input parameters and the obtained responses. In modeling of manufacturing processes using RSM, the sufficient data is collected through designed experimentation. An experiment is designed with 2^k (where, k = number of parameters, in this study k =4) factorial with central composite-second order ratable design is used. This consists of number of corner points =16, number of axial points=8, and a centre point at zero level =4. The axial points are located in a coded test condition space through parameter 'α'. For the design to remain rotatable, 'α' is determined as $(2^k)^{1/4} = 2$. Thus the coded level for the axial points is at 2. The center point is repeated four times to estimate the pure error. The coded value corresponding to actual value for each process parameter is derived using following formula:

$$\text{Coded test condition} = \frac{\text{Actual test condition} - \text{mean test condition}}{\text{Range of test condition/2}} \quad (1)$$

As an illustration, if actual test condition of 'pulse on time (T_{on})' is 5 then, the corresponding coded value is [5-((4+8)/2)] / [(8-4)/2] = -0.5.

The coded numbers are thus obtained from following transformation equations:

$$x_1 = \frac{T_{on} - T_{on_0}}{\Delta T_{on}} \quad (2)$$

$$x_2 = \frac{T_{off} - T_{off_0}}{\Delta T_{off}} \quad (3)$$

$$x_3 = \frac{I_p - I_{p_0}}{\Delta I_p} \quad (4)$$

$$x_4 = \frac{F - F_0}{\Delta F} \quad (5)$$

Where, x_1, x_2, x_3 and x_4 are the coded values of the parameters T_{on}, T_{off}, I_p, and F respectively. T_{on0}, T_{off0}, I_{p0}, and F_0 are the values of pulse on time, pulse off time, peak current, and servo feed setting at zero level. ΔT_{on}, ΔT_{off}, ΔI_p and ΔF are, the intervals of variation in T_{on}, T_{off}, I_p, and F respectively. The experimental set up details are given below:

- Machine type/make: CNC-WEDM, Elektra ELPULSE-30

- Wire material: Brass
- Wire diameter: 0.25 mm
- Wire tension: 8 N
- Dielectric fluid: Deionised water
- Workpiece specification: Rectangular, cavity of size: 60x110x12 mm, OHNS
- Surface roughness measuring device: Hommel tester T-500

Table I shows coded values of process parameters. Table II shows the experimental matrix.

Table I: Coded values of process parameters.

Coded values	-2	-1	0	+1	+2
Pulse on time	2	4	6	8	10
Pulse off time	6*	10	20	30	40
Peak current	65	90	115	140	165
Servo feed	20	30	40	50	60

*although the coded value is '0' by using equation (1), the minimum possible value is '6'.

Table II: Design of experiments and the results.

S.N.	T_{on} (µs)	T_{off} (µs)	I_p (Amp)	F	V_m(mm/min)	R_a (µm)
1	-1	-1	-1	-1	1.15	1.6
2	1	-1	-1	-1	1.5	2.5
3	-1	1	-1	-1	0.93	1.5
4	1	1	-1	-1	1.16	1.8
5	-1	-1	1	-1	1.54	2.2
6	1	-1	1	-1	1.58	2.3
7	-1	1	1	-1	1.13	1.7
8	1	1	1	-1	1.3	2.0
9	-1	-1	-1	1	1.58	2.3
10	1	-1	-1	1	1.9	3.7
11	-1	1	-1	1	1.05	1.5
12	1	1	-1	1	1.48	2.4
13	-1	-1	1	1	1.9	3.1
14	1	-1	1	1	1.57	2.4
15	-1	1	1	1	1.1	1.5
16	1	1	1	1	1.28	2.1
17	0	0	0	0	1.55	3.4
18	0	0	0	0	1.55	4.0
19	0	0	0	0	1.56	3.5
20	0	0	0	0	1.56	3.5
21	2	0	0	0	1.75	3.3
22	-2	0	0	0	1.13	1.6
23	0	2	0	0	1.35	1.8
24	0	-2	0	0	1.95	2.6
25	0	0	2	0	1.6	1.2
26	0	0	-2	0	0.81	3
27	0	0	0	2	1.7	1.6
28	0	0	0	-2	0.95	3.7

To study the effect of process parameters i.e. T_{on}, T_{off}, I_p, and F, on performance measures i.e. machining speed (V_m) and surface roughness (R_a), a second-order polynomial response is fitted into the following equation.

$$y = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_{ii} x_i^{\,2} + \sum_{j>1}^{k} b_{ij} x_i x_j \qquad (6)$$

Where 'y' is the response and the x_i (1, 2… k) are coded level of k quantitative parameters. The coefficient b_0 is the free term, the coefficients b_i are the linear terms, the coefficients b_{ii} are the quadratic terms, and the coefficients b_{ij} are the interaction terms. Equation (7) and equation (8) are then derived by determining the values of the coefficients using the least square technique for the observations collected as shown in Table 2, for machining speed (V_m) and surface roughness (R_a) respectively.

$$V_m = 1.555 + 0.1095x_1 - 0.187x_2 + 0.0929x_3 + 0.1279x_4 + 0.0393x_1x_2 - 0.0793x_1x_3 - 0.01188x_1x_4 - 0.01688x_2x_3 - 0.0493x_2x_4 - 0.0606x_3x_4 - 0.03219x_1^2 + 0.02031x_2^2 - 0.0909x_3^2 - 0.06094x_4^2 \qquad (7)$$

$$R_a = 3.6 + 0.2979x_1 - 0.2979x_2 - 0.1479x_3 - 0.03542x_4 + 0.021875x_1x_2 - 0.2031x_1x_3 + 0.04062x_1x_4 + 0.01562x_2x_3 - 0.1531x_2x_4 - 0.1031x_3x_4 - 0.3182x_1^2 - 0.3807x_2^2 - 0.4057x_3^2 - 0.2682x_4^2 \qquad (8)$$

To test whether the data are well fitted in model or not, the calculated S value of the regression analysis for machining speed and surface roughness are obtained as 0.148 and 0.644 respectively, which are smaller and R value for both the responses are 0.89 and 0.71, respectively. The R value is moderately high for machining speed and is moderate for surface roughness. Hence, the model fits the data.

Now an advanced optimization method based on PSO algorithm is used to optimize Wire-EDM process parameters. The next section briefly describes the algorithm.

4. PARTICLE SWARM OPTIMIZATION (PSO)

Particle swarm optimization (PSO) is an evolutionary computation technique developed by Kennedy and Eberhart [17]. It exhibits common evolutionary computation attributes including initialization with a population of random solutions and searching for optima by updating generations. Potential solutions, called particles, are then "flown" through the problem space by following the current optimum particles. Each particle keeps track of its coordinates in the problem space, which are associated with the best solution (fitness) it has achieved so far. This value is called 'pBest'. Another "best" value that is tracked by the *global* version of the particle swarm optimization is the overall best value and its location obtained so far by any particle in the population. This location is called 'gBest'. The particle swarm optimization concept consists of, at each step, changing the velocity (i.e. accelerating) of each particle toward its 'pBest' and 'gBest' locations (global version of PSO). Acceleration is weighted by a random term with separate random numbers being generated for acceleration toward 'pBest' and 'gBest' locations. The updates of the particles are accomplished as per the following equations.

$$V_{i+1} = w * V_i + c_1 * r_1 * (pBest_i - X_i) + c_2 * r_2 * (gBest_i - X_i) \qquad (9)$$

$$X_{i+1} = X_i + V_{i+1} \qquad (10)$$

Equation (9) calculates a new velocity (V_{i+1}) for each particle (potential solution) based on its previous velocity, the best location it has achieved (‘*pBest*’) so far, and the global best location (‘gBest’), the population has achieved. Equation (10) updates individual particle's position (X_i) in solution hyperspace. The two random numbers ‘r_1’ and ‘r_2’ in equation (9) are independently generated in the range [0, 1].

The acceleration constants ‘c_l’ and ‘c_2’ in equation (9) represent the weighting of the stochastic acceleration terms that pull each particle towards ‘pBest’ and ‘gBest’ positions. ‘c_1’ represents the confidence the particle has in itself (cognitive parameter) and ‘c_2’ represents the confidence the particle has in swarm (social parameter). Thus, adjustment of these constants changes the amount of tension in the system. Low values of the constants allow particles to roam far from target regions before being tugged back, while high values result in abrupt movement toward, or past through target regions [18, 19]. The inertia weight ‘*w*’ plays an important role in the PSO convergence behaviour since it is employed to control the exploration abilities of the swarm. The large inertia weights allow wide velocity updates allowing to globally explore the design space while small inertia weights concentrate the velocity updates to nearby regions of the design space. The optimum use of the inertia weight “*w*” provides improved performance in a number of applications. The effect of w, c_1 and c_2 on convergence for standard numerical benchmark functions is provided by Bergh and Engelbrecht [20].

Unlike genetic algorithm, PSO algorithm does not need complex encoding and decoding process and special genetic operator. PSO takes real number as a particle in the aspect of representation solution and the particles update themselves with internal velocity. In this algorithm, the evolution looks only for the best solution and all particles tend to converge to the best solution. In the implementation process, particles randomly generated at the beginning or generated by internal velocity during the evolutionary process usually violate the system constraints resulting in infeasible particles. Therefore, the handling of system constraints, particularly nonlinear equation constraints, and the measurement and evaluation of infeasible particles is very important. To cope with constrained problems with evolutionary computation, various approaches such as rejection of infeasible individuals, repair of infeasible individuals, replacement of individuals by their repaired versions, and penalty function methods can be adopted. Among them, the penalty function methods are particularly promising as evidenced by recent developments [19].

Wire EDM process is discussed in the next section to demonstrate and validate the proposed particle swarm optimization algorithm with constant values of inertia weight and acceleration coefficients.

5. EXAMPLE

Now to demonstrate and validate the PSO algorithm, an example is considered for the optimization of wire electric discharge machining process parameters, based on the model developed in section 3.

5.1 Objective function

Maximize V_m (as given by equation (7))

5.2 Constraint

Constraint is to ensure that the surface roughness value (R_a) should not exceed permissible surface roughness (R_{per}) as specified by equation (11) below.

$$R_{per} - R_a \geq 0 \qquad (11)$$

Where, R_a is the surface roughness value as specified by equation (8).

5.3 Parameters and parameter bounds

The four process parameters considered in the present work are Pulse on time (T_{on}), Pulse off time (T_{off}), Peak current (I_p), Servo feed setting (F).The upper and lower bound values for these parameters are as given below.

$$4 \leq T_{on} \leq 8 \text{ μs} \tag{12}$$

$$10 \leq T_{off} \leq 30 \text{ μs} \tag{13}$$

$$90 \leq I_p \leq 140 \text{ amp} \tag{14}$$

$$30 \leq F \leq 50 \tag{15}$$

Now, the PSO algorithm is applied to solve the above optimization problem. The optimum selection of operating parameters of the algorithm like acceleration constants 'c_1' and 'c_2' as well as inertia coefficient 'w' is very essential for convergence of the algorithm. To ensure the convergence of PSO algorithm, the condition specified by equation (16) must be satisfied [20].

$$\max (|\lambda_1|, |\lambda_2|) <1 \tag{16}$$

Where, λ_1 and λ_2 are the eigen values given by equations (17) and (18).

$$\lambda_1 = (1+ w - \phi_1 - \phi_2 +\gamma) / 2 \tag{17}$$

$$\lambda_2 = (1+ w - \phi_1 - \phi_2 - \gamma) / 2 \tag{18}$$

$$\text{and } \gamma = [(1+ w - \phi_1 - \phi_2)^2 - 4w)]^{1/2} \tag{19}$$

Also, $\phi_1= r_1*c_1$ and $\phi_2= r_2*c_2$

Considering the feasible range for the value of '$\phi_1 + \phi_2$' as 0 to 4 and that for 'w' as 0 to 1, it can be observed that for convergent trajectories the relation given by equation (20) must be satisfied.

$$w > 0.5 (\phi_1 + \phi_2) -1 \tag{20}$$

Now, in the present study the following values of 'w', 'c_1' and 'c_2' are used.

- Inertia weight factor (w) = 0.65
- Acceleration coefficients: c_1 = 1.65 and c_2 = 1.75

Considering the extreme possibility of random number as 'r_1'=0.95 and 'r_2'=0.95, the right hand term in equation (20) is 0.5*(0.95*1.65 + 0.95*1.75) –1 = 0.61, which is less than 0.65 thus satisfies the equation (20). Hence, the values of 'w', 'c_1' and 'c_2' selected in the present work are appropriate for convergence of the algorithm.

Table III shows the optimum values of process parameters for various values of surface roughness as per the customer requirement.

Table III: Results of optimization using PSO for various permissible values of R_a.

R_{per} (μm)	T_{on} (μs)	T_{off} (μs)	I_p (Amp)	*F*	V_m (mm/min)	R_a (μm)
2.0	8	30	132.52	50	1.422	2.0
2.1	4	21.65	140	50	1.465	2.1
2.2	4	19.68	140	50	1.522	2.2
2.3	4.1	10	140	50	1.827	2.3
2.4	4	10	135.75	50	1.835	2.4

For R_{per} = 2.0 μm, Optimality of the above mentioned solution could be confirmed from the Figures 2 to 5. Figure 2 shows the variation of machining speed and constraint with pulse on time. As shown in Figure 2, the machining speed increases with increase in pulse on time; hence higher value of pulse on time is desired. Thus the selection of upper bound value of pulse on time T_{on} = 8 μs is appropriate. It is also observed that the surface roughness initially increases and then decreases with pulse on time. Hence, the constraint is initially violated beyond value of $T_{on} \cong$ 5.3μs, however, it is satisfied again at T_{on} = 8μs. Variation of machining speed and constraint with pulse off time is shown in Figure 3. As shown in Figure 3, machining speed decreases but surface finish increases with the increase in pulse off time. Thus, from machining speed point of view, lower value of pulse off time is desired. However, upper bound value (30 μs) of pulse off time is selected as for any value below 30 μs, surface roughness constraint is violated.

Figure 4 shows variation of machining speed and constraint value with peak current. The machining speed initially increases slightly with peak current up to certain value (≅107 amps) and then decreases with increases in peak current. Values of peak current up to 107 amp can't be selected as for these values the constraint is violated. From this point of view lower value of peak current should be selected. As the value selected for peak current of 132.52 amp is the lowest value at which the constraint is satisfied, is appropriate. Figure 5 shows variations of machining speed and constraint value with servo feed setting. It is observed from Figure 5, that servo feed setting has less effect on machining speed, but affects the surface roughness significantly. Better surface finish can be achieved for higher value of servo feed setting. From this point of view, selection of upper bound value of servo feed setting (=50) is appropriate.

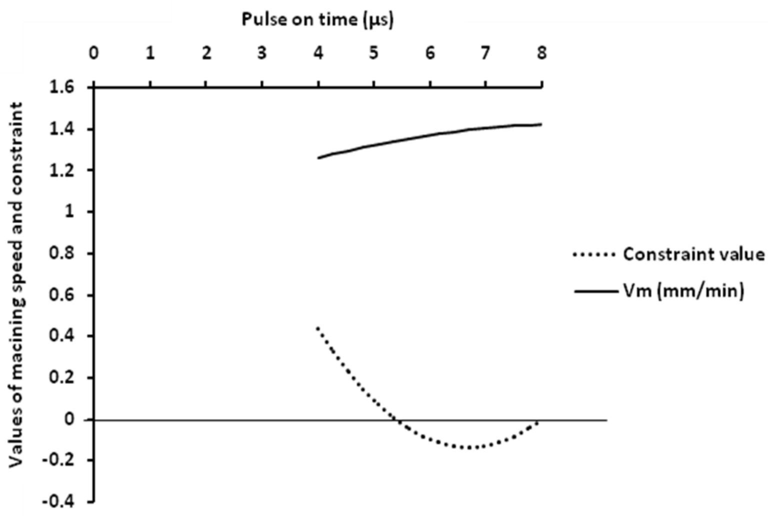

Figure 2: Variation of machining speed and constraint value with pulse on time.

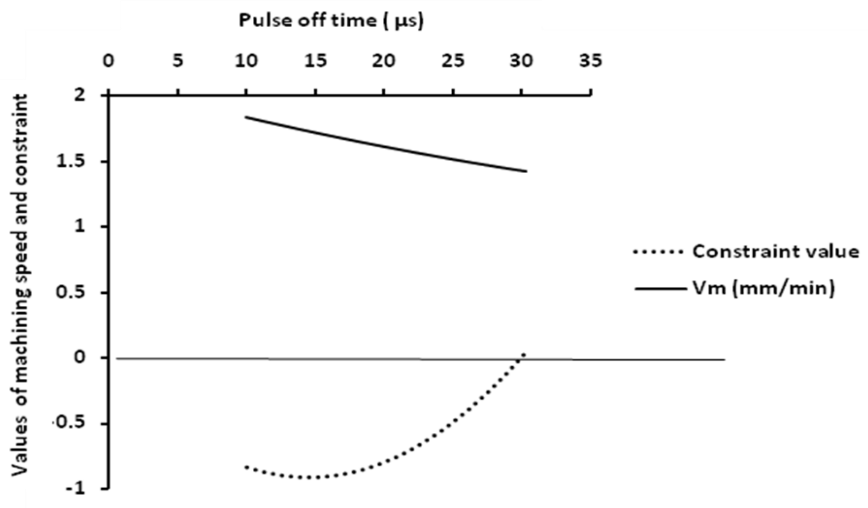

Figure 3: Variation of machining speed and constraint value with pulse off time.

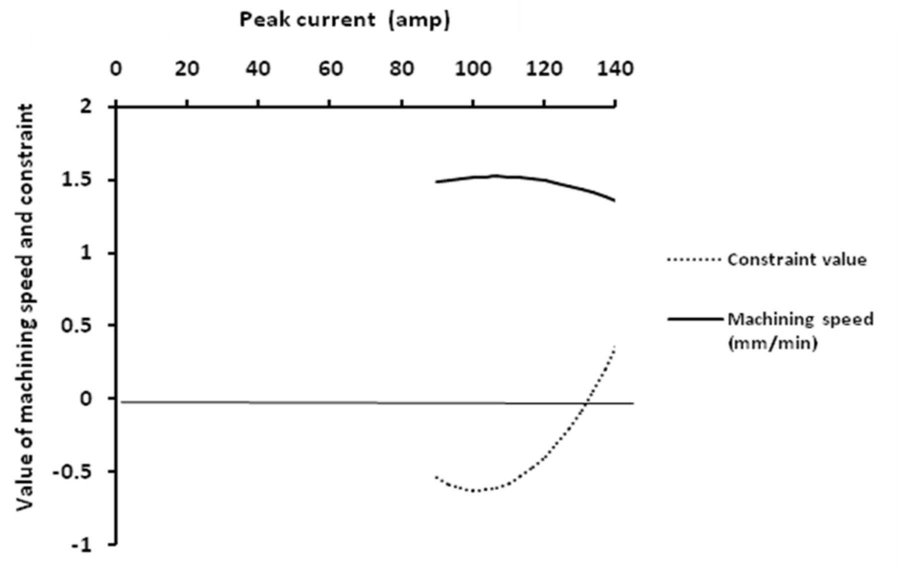

Figure 4: Variation of machining speed and constraint value with peak current.

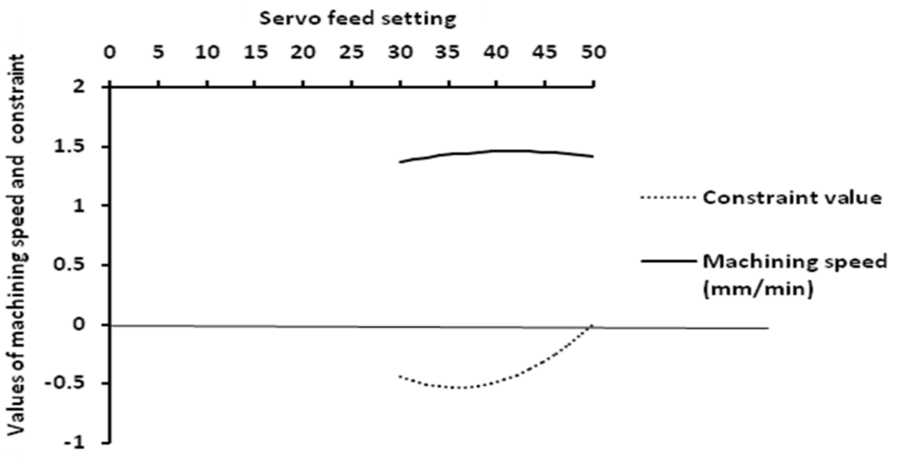

Figure 5: Variation of machining speed and constraint value with servo feed setting.

The model formulated in this work is highly multi-modal as it has number of local optima. As an illustration, for desired value of R_a = 2.1μm, one of the local optimum solution is: T_{on}=4, T_{off} = 10, I_p=90, and F = 31 with corresponding value of V_m=1.106 mm/min and constraint value zero thus showing no scope for further improvement. However, the global optimum solution obtained using PSO provides V_m=1.465 mm/min, showing about 32% improvement over the local optimum solution which is generally obtained by using traditional methods of optimization. This clearly justifies the use of non-traditional optimization algorithm like PSO as in present study, to solve such multi-modal problem.

6. CONCLUSIONS

Modeling and optimization aspects of wire electric discharge machining process parameters are considered in the present work. The objective considered is maximization of machining speed subjected to constraint of surface roughness. Mathematical models have been developed based on RSM approach for correlating the combined effects of pulse on time, pulse off time, peak current and servo feed setting on machining speed and surface roughness. The optimum setting of the process parameters is then obtained using a non-traditional optimization technique namely, particle swarm optimization. Compared to other non-conventional optimization methods, few trials are required to predict the best and worst operating parameters of particle swarm optimization algorithm. Furthermore, the particle swarm optimization algorithm requires only 30 to 40 iterations for convergence to the optimal solution. The algorithm can also be easily modified to suit optimization of process parameters of other non-traditional machining processes such as electro-chemical machining, laser beam machining, plasma arc machining, etc.

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DYNAMIC CELLULAR MANUFACTURING SYSTEMS DESIGN - A COMPREHENSIVE MODEL & HHGA

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Abstract:
Today's product demand and mix changes requiring reconfiguration of cells in each period of a multi-period planning horizon, This paper proposes a mixed-integer non-linear programming model for reconfigurable CMS design to meet changes in product mix & demand in each period of a multi-period planning horizon. The proposed model, to the best of author's knowledge, is the most comprehensive model to date with more integrated approach. The proposed DCMS model integrates concurrently the important manufacturing attributes in existing models in a single model such as machine breakdown effect - machine repair & production time loss cost; production planning - part inventory holding, internal production cost & outsourcing cost; Process batch size; transfer batch sizes for intra-cell travel & inter-cell travel; lot splitting; alternative process plan & routing, sequence of operation; multiple copies of identical copies; machine capacity, cutting tooling requirements, work load balancing, machine in different or same cell constraint; machine procurements, multi- periods dynamic cell reconfiguration . It also includes various costs. A Hybrid Hierarchical Genetic Algorithm (HHGA) is also designed to solve the model for some examples taken from existing literature. Our experience shows that HHGA needs much less computational time than LINGO-based solution approach. Further, we intend to enhance the model with attributes such as production control, selection of material handling equipment and equipment layout etc. As a practical application of this work, the academician, the designer and managers of cellular manufacturing systems will find this work useful for design/ redesign of cells in their plants or research work.

Key Words: DCMS, Mixed-integer programming, Breakdown effects, Production planning

1. INTRODUCTION & LITERATURE ON DCMS

Due to the present competitive market, batch manufacturing needs to produce a large variety of products in small lot sizes at a competitive price with variable demand & product mix from period to period. Conventional manufacturing systems (job shops and flow shops) have resorted to group technology (GT) as a viable alternative to overcome these difficulties and to gain economic benefits of mass production systems & the flexibility of job shops .The best cell formation for one period may not be efficient for subsequent periods. A promising technique to overcome this problem is dynamic reconfiguration. Therefore, there is increasing thrust for research to develop models and solution procedures for dynamic cell reconfigurations over multiple times periods.

The literature on the CMS design is extensive. Besides other authors, a comprehensive review is presented by Balakrishnan and Cheng [1].Lokesh & Jain [2] presented an algorithm APOSTVUIT [2] with important production data for single period. Lokesh & Jain [3] also presented an algorithm APORVUIT [3] and also concluded the need of CMS reconfiguration with change in product mix & demand. In the most of the published article reviewed by us, the cell formation problems have been considered under static conditions [2, 3 etc.] to form cells for a single time period with constant demand and product mix. A list of attributes typically included in CMS/DCMS models is given in Table-I. Lokesh & Jain [4] also developed a DCMS model having 33 attributes with comparison to 38 models of other researchers. Here, due to page limit, we present a sample of 16 recently published articles with their attributes in Table-II[5 to 19].

Seifoddini H & Alhourani F [20] emphasized that about 75% of all manufacturing units are engaged in batch production of a large variety of parts in small batches. In real production systems the parts are move in the form of batches. Therefore, it is misleading to consider the intracellular & intercellular movements of individual parts instead of the intracellular & intercellular movements of batches [20].

A very few researchers included transfer batch sizes & intracellular movement costs , production planning issues such as part inventory holding cost , part outsourcing costs, lot splitting etc. in their DCMS models.

Machine breakdown effects: An important desirable aspect of CM systems is to include the effect of machine breakdowns in the model. Traditionally, cell formation & work allocation is done with assumption of 100% reliability of machines. In practice, machines fail during operations. Machine failures creates greatest impact on due dates and other performance criteria, even if existence of alternative routes of the parts to alternative workstations. Jabal Ameli MS et al. [9] proposed that the reliability effect may be modeled as machine repair costs and production time delay costs.

Machine repair costs: Let the breakdown time for a machine, *m* has an exponential distribution with a known failure rate $\lambda(m)$, the reliability, over production time t, $R(m,t)=exp(-\lambda\ (m)\ t)$ & the number of machine breakdown $N(m,t)$,$N(m,t) = t/MTBF(m)$. Production time *t* on a machine *m* for operation *o* of part *p* is product of operation time of part *p* on machine *m* and number of parts (ie. Production demand of part *p*) for processing on machine *m* .Break down cost) of a machine *m* in time *t*, the mean time between failures MTB *F (m)*, unit breakdown cost of machine *B(m)* is:

$$BC(p,m)= \{ (\text{Production demand} * \text{operation time} * B(m))/MTBF(m) \} \quad (1)$$

Total breakdown cost of a part *p* for a route R_p , $\{ m^1 (p,R_p), m^2 (p,R_p),\ldots\ldots, m^{M(p,R_p)}(p,R_p)\}$ is sum of breakdown costs on each machines in route, R_p . For part *p*. $m^2 (p,R_p)$, $M(p,R_p)$ are second machine ,total number of machines in route R_p, respectively Grand breakdown cost(GBC) is sum of total breakdown cost for all parts [9].

Time-based effects [9]: A significant amount of time is usually spent to repair a machine in breakdown. Let repair time for each machine follows an exponential distribution with a known repair rate $\mu(m)$, mean time to repair MTTR (m). The total repair time of machine *m*:

$$RT(m ,t)=\{[t * MTTR(m)]/MTBF(m)\} \quad (2)$$

For the total processing time (TPT) for a machine, its repair time is added to the production time of machine. Also, for the total processing time of a process routing, TPT for each machine is added.

Genetic algorithm: Several authors such as Defersha & Chen [12] used genetic algorithm to solve CMS problem. Chromosome, here, do not has coding for part inventory held. This model assumes one operation of a part completed in one cell only. It reduces routing flexibility to respond machine breakdowns. Chromosome coding also needs this improvement. They considered lengthy coding scheme. Due to single point crossover, cut section of chromosome passes through single point i.e. through one period. After single point crossover, genes in other period remain as before. The model presented in this paper considers a larger coverage of the attributes, a wider range of input data and cell formation criteria than other’s models. The model presented in this paper considers 33 attributes given in Table-I. A Hybrid Hierarchical Genetic Algorithm (HHGA) is also designed to solve the model for some examples.

Table I: CMS design attributes in the proposed model & other's models.

Ab	1	1	2	2	3	4	4	5	6	7	7	8	8	9	9	10	10	11	11	12	12	13
Rn	a	b	A	b		A	b			a	b	a	b	a	b	a	b	a	b	A	b	
Pm		√	√		√	√		√	√	√	√	√		√		√		√	√	√		
4		√	√		√	√		√	√	√	√	√		√		√		√	√	√		
5		√	√		√							√						√	√	√		
6		√	√		√							√						√	√	√		
7		√	√		√							√				√		√	√			
8			√		√							√			√	√		√				
9		√	√									√				√		√	√			
10		√	√		√	√		√	√	√	√	√		√		√		√				
11		√	√		√	√		√	√	√	√	√		√		√		√				
12		√	√		√	√		√	√	√	√	√		√		√		√				
13		√	√		√	√		√	√	√	√	√		√		√		√				
14			√		√							√				√		√				
15		√										√				√		√	√			
16			√		√							√				√		√				
17			√		√							√				√		√				
18			√		√							√				√		√				
19																√		√				

Table I: Continue… (Ab- Attributes; Ta-total Attributes; Rn -Reference No. ; Pm – Present Model).

Ab		14	15	15	16	17	18	19	20	21	22	22	23	24	24	24	25	26	27	28	Ta.
Rn			A	b							a	b		a	b	c					
Pm		√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	33
4		√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	33
5		√	√			√			√	√			√			√	√	√	√		17
6		√	√		√	√			√	√			√			√	√	√	√		18
7		√			√				√		√	√						√	√		14
8		√																√	√	√	10
9														√		√				√	9
10		√	√	√	√	√	√	√	√									√	√	√	23
11		√	√	√	√	√	√	√	√									√	√	√	23
12		√	√	√	√	√	√	√	√	√								√	√	√	24
13		√	√	√	√	√	√	√	√	√								√	√	√	24
14		√	√	√	√			√			√	√									12
15		√	√			√															8
16																					5
17		√	√	√	√			√													10
18		√	√	√	√			√													10
19		√	√	√				√													6

Period-1 →	Part -1	Part -4	Part -5	Part -6	Part -7	Part -8
Period-2 →	Part -1	Part -2	Part -4	Part -6	Part -7	Part -8
Period-3 →	Part -1	Part -3	Part -5	Part -6	Part -7	Part -8

Figure 1: Structure of chromosome of 8 parts X 3 time periods.

Table II: List of manufacturing attributes.

1. Alternative routing
(a) Selecting the best route
(b) Allowing alternative routing coexist
 (a) Deterministic
(b) Probabilistic
3. Dynamic cell reconfiguration
4. Workload balancing
(a) Inter-cell workload
(b) Intra-cell workload
5. Types of tools required by a part
6. Types of tools available on a machine
7. Machine proximity
(a) Separation constraint
(b) Collocation constraint
8. Sequence of operation
(a) Used as input for determine magnitude of material flow
(b) Used as similarity measure between parts
9. Setup cost/time
(a) Setup cost
(b) Setup time
10. Cell/part family size constraint(a) Cell size constraint
(b) Part family size constraint
11. Movement of parts (material handling cost)
(a) Inter-cell movement
(b) Intra-cell movement
12. Facility layout
(a) Inter-cell layout
(b) Intra-cell layout
13. Operator allocation
14. Machine capacity
15. Identical machines
a) Within a cell
(b) In the entire system
16. Machine investment cost
17. Subcontracting cost
18. Tool consumption cost
19. Unit operation time
20.Machine Operation cost
21. Lot splitting
22. Transfer batch size
(a) Inter-cell movement
(b) Intra-cell movement
23. Part holding cost
24.Breakdown effect to incorporate Reliability modelling
25. Internal production overhead cost
26. multi-period planning
27. Machine relocation cost
28. Process batch size
(a) machine repair cost
(b) maintenance overhead cost
(c) Production time increase on machine due to machine downtime

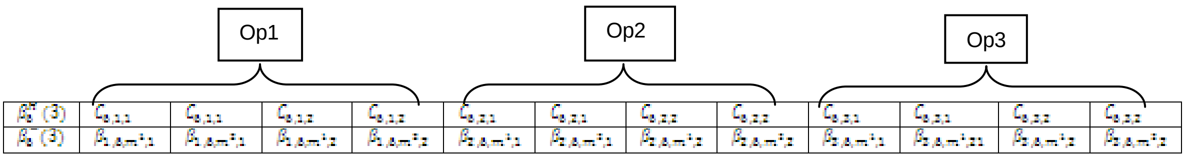

Figure 2: Details of coding scheme of part-6 in time period-3.

2. PROBLEM FORMULATION

We conceive a manufacturing system comprising of a number of machines to process different parts. A part may need some or all of the tools available on a given machine. A part may undergo through several operations in a given sequence as numbered. An operation of a part can be processed by a machine having available required tool. Having tool availability with more than one machine type, the machines are supposed as alternative routings for processing the part. The processing time for all operations of a part type on different machine types are known and deterministic. The demand for each part type in each period is known and deterministic. The capabilities and time-capacity of each machine type are known and constant over the planning horizon. Parts are moved between and within cells as batch. As mentioned earlier, inter- inter- and intra-cell batches have different costs and sizes. Part inventory held is zero in beginning & at the end of planning horizon. Backorders are not allowed. The manufacturing environment is described in detail in the paper [4].Due to page limit of journal; it is not possible to give full description.

2.1 Notations for Indices & Input data

Time period index is $t = 1,2,...,T$. Part type index is $p= 1,2,...,P$. Index of operations of part p is $o= 1, 2,...,O_p$. Machine index is $m= 1,2,...,M$. Tool index is $c_t= 1,2,...,C_t$. Cell index is $k= 1,2,...,K$.P is number of part types .O_p is number of operations for part p. M is number of machine types. K is maximum number of cells that can be formed. $D_p(t)$is demand for part p in time period t. D_p^i is Demand of part p for internal production in time period t. B_p^{intra} is Transfer batch size for intra-cell movement of part p in time period t. B_p^{inter} is Transfer batch size for inter-cell movement of part p. B^b is Process batch size for part p .V_p^{inter} inter-cell movement cost per Transfer batch of part p. V_p^{intra} is intra-cell movement cost per Transfer batch of part p ,(To Justify CMS, it is supposed that $\{V_p^{intra} / B_p^{intra}\}<\{V_p^{inter} / B_p^{inter}\}$ $\forall$ p. OS_p is cost of outsourcing part p . λ_{opc_t} = 1, if operation o of part p needs tool c_t,=0, otherwise. δ_{ctm} = 1, if tool c_t is available on machine m=0, otherwise. t_{opm} is processing time of operation o of part p on machine type m. SU_{opm} is setup cost for operation o of part p on machine type m. TC_{opm} is tool consumption cost of operation o of part p on machine type m. $N_m(t)$ is maximum number of machine type m that can be procured at beginning of period t. $AC_m(t)$ is Acquisition cost of machine type m at beginning of period t . OP_m is operation cost per hour of machine type m. OV_m is Machine maintenance overhead cost of machine type m per unit time in time period t for reliability consideration. OH_m is Machine breakdown cost of machine type m per unit time in time period t for reliability consideration. $MTBF(m)$ is mean time between failures for machine m for time period t .MTTR(m) is mean time to repair for machine m for time period t . λ (m) is failure rate for machines m for reliability consideration. $\mu(m)$ is repair rate for machines m for reliability consideration. T_m is time capacity of one machine of type m for one time period t. LL_k is minimum number of machines limit in cell k. UL_k is maximum number of machines limit in cell k. R_m^+ is relocation cost of installing one machine of type m. R_m^- is relocation cost of removing one machine of type m. q is $0 \le q < 1$; a factor for work load of a cell being as low as $qx100\%$ from the average workload per cell. $L_p(t)$ is the number of cells among which an entire lot of part p may split into during time period for processing of certain operation; $L_p(t) \in \{1,2,................\}$. L^p is a large positive number . M_a^p is a set of machine pairs $\{(m^a, m^b)/m^a, m^b \in (1,......,M), m^a \neq m^b$, and m^a cannot be is placed in the same cell with $m^b\}$. M_n^p is a set of machine pairs $\{(m^c, m^d)/m^c, m^d \in (1,......,M), m^c \neq m^d$, and m^c should be placed in the same cell with $m^d\}$. PH_p is Part holding cost per part type p per time period t. $A_m(t)$ is Quantity of machine type m available at time period t .

2.2 General integer Decision Variable & Auxiliary binary Decision variables

$N_{mp}(t)$ is number of type *m* machines to present at cell *k* at beginning of period *t* . $Y^{+}_{mk}(t)$ is number of type *m* machines added in cell *k* at beginning of period *t* . $Y^{-}_{mk}(t)$ is number of type *m* machines removed from cell *k* at beginning of period *t*. $Q_p(t)$ is number of parts *p* to be subcontracted at time *t*. $Q_n(t)$ is number of part inventory of type *p* kept in period and carried over to period *(t+1)*. $X_{opmk}(t)$ is number of parts of type *p* processed by operation *o* on machine type *m* in cell *k* at time *t* . $PN_m(t)$ is number of machine type *m* procured at time *t* . $PA_m(t)$ is Quantity of machine type m available in time period *t* with accounting for machines procured in previous period. $\beta_{opmk}(t)$ is the proportion of total demand of part *p* with the *o*^th^ operation to perform by machine *m* in cell *k* during period *t* . $\overline{\beta}_p(t)$ is the proportion of total demand of part *p* to be outsourced in time period *t*. Logical constrains forming Auxiliary binary Decision variables' values are not required to make decisions for system configuration and operation assignments. $\mu_{mp}(t)=1$, if type *m* machines are to be allocated to cell *k* during time period *t, = 0*, otherwise. $\nu_{opk}(t)=1$, if operation *o* of part *p* is to be performed in cell *k* during time period *t, = 0,* otherwise $z_{opmk}(t)=1$, if operation *o* for part type *p* is carried out on machine type *m* in cell *k* at time *t ,= 0*, otherwise

2.3 Objective (Z) & Constraints of Mixed Integer Programming Model

$$\text{Minimize } Z=\sum_{t=1}^{T}\sum_{m=1}^{M}AC_m(t).\{\,PA_m(t)-PA_m(t-1)\}+\sum_{t=1}^{T}\sum_{k=1}^{K}\sum_{m=1}^{M}\left[OV_m(t).+\frac{D^i_p(t).\beta_{opmk}(t).t_{opm}}{MTBF(m)}\right].OH_m(t)+$$
$$\sum_{t=1}^{T}\sum_{p=1}^{P}Q^H_p(t).PH_p+\sum_{t=1}^{T}\sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{p=1}^{P}\sum_{o=1}^{O_p}\frac{D^i_p(t).\beta_{opmk}(t)}{B^b_p}..SU_{opm}+\sum_{t=1}^{T}\sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{p=1}^{P}\sum_{o=1}^{O_p}D^i_p(t).\beta_{opmk}(t).TC_{opm}+$$
$$\sum_{t=1}^{T}\sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{p=1}^{P}\sum_{o=1}^{O_p}D^i_p(t).\beta_{opmk}(t).t_{opm}\left[1+\frac{MTTR(m)}{MTBF(m)}\right].OP_m+\sum_{t=1}^{T}\sum_{k=1}^{K}\sum_{m=1}^{M}R^{+}_m.Y^{+}_{mk}(t)+\sum_{t=1}^{T}\sum_{k=1}^{K}\sum_{m=1}^{M}R^{-}_m.Y^{-}_{mk}(t)+$$
$$\frac{1}{2}\sum_{t=1}^{T}\sum_{p=1}^{P}\sum_{o=1}^{O_p-1}\sum_{k=1}^{K}\left[\frac{D^i_p(t)}{B^{\text{inter}}_p}\right]\gamma^{inter}_p\left(\left|\sum_{m=1}^{M}\beta_{(o+1).pmk}(t)-\sum_{m=1}^{M}\beta_{opmk}(t)\right|\right)+\sum_{t=1}^{T}\sum_{p=1}^{P}Q^o_p(t).OS_p+$$
$$\frac{1}{2}\sum_{t=1}^{T}\sum_{p=1}^{P}\sum_{o=1}^{O_p-1}\sum_{k=1}^{K}\left[\frac{D^i_p(t)}{B^{\text{intra}}_p}\right]\gamma^{intra}_p\left(-\left|\sum_{m=1}^{M}\beta_{(o+1).pmk}(t)-\sum_{m=1}^{M}\beta_{opmk}(t)\right|+\sum_{m=1}^{M}\left|\beta_{(o+1).pmk}(t)-\beta_{opmk}(t)\right|\right) \quad (3)$$

Objective, Z is subject to constraints as follows:

$$X_{opmk}(t)\le L^b.z_{opmk}(t) \quad (4)$$

$$z_{opmk}(t)\le X_{opmk}(t) \quad (5)$$

Where $Q^o_p(t)=\overline{\beta_p}(t).D_p(t)$ (7)

Where $X_{opmk}(t)=\beta_{opmk}(t).D^i_p(t)$ (8)

$$\beta_{opmk}(t)\le\lambda_{opc_t}.\delta_{c_tm};\forall(p,o,m,k,t) \quad (9)$$

$$\sum_{m=1}^{M}\beta_{opmk}(t)\le\nu_{opk};\forall(p,o,k,t) \quad (10)$$

$$\sum_{k=1}^{K}N_{mk}(t)-\sum_{k=1}^{K}N_{mk}(t-1)\le N_m(t);\forall(m,k) \quad (13)$$

$$D^i_p(t)+Q^H_p(t-1)-Q^H_p(t)+Q^o_p(t)=D_p(t) \quad (6)$$

Where $D^i_p(t)=\sum_{m=1}^{M}\sum_{k=1}^{K}X_{opmk}(t);\forall(p,o,t)$

$$\sum_{k=1}^{K}\nu_{opk}(t)\le L_p(t);\forall(p,o,t) \quad (11)$$

$$T_mN_{mk}(t)\ge\sum_{p=1}^{P}\sum_{o=1}^{O_p}D^i_p(t).\beta_{opmk}(t).t_{opm};\forall(m,k,t) \quad (12)$$

$$N_{mk}(t)=N_{mk}(t-1)+Y^{+}_{mk}(t)-Y^{-}_{mk}(t);\forall(m,k,t) \quad (14)$$

$$LB_k \le \sum_{m=1}^{K} N_{mk}(t)\le UB_k,\forall(m,k,t) \quad (15)$$

$$N_{pmk}(t)\le L^b.\mu_{mk}(t);\forall(m,k,t) \quad (16)$$

$$\mu_{mk}(t)\le N_{mk}(t),\forall(m,k,t) \quad (17)$$

$$\mu_{mk}(t)+\nu_{mk}(t)\le 1;(m^a,m^b)\in S^{dk}\forall(k,t) \quad (18)$$

$$\mu_{mk}(t)-\nu_{mk}(t)\le 0;(m^c,m^d)\in S^{sk}\forall(k,t) \quad (19)$$

$$0\le\overline{\beta}_p(t)\le 1,\forall(p,t) \quad (20)$$
$$0\le\beta_{opmk}(t)\le 1,\forall(o,p,m.k,t)$$
$$0\le\beta^H_p(t)\le 1,\forall(p,t)$$

$$\sum_{m=1}^{M}\sum_{p=1}^{P}\sum_{o=1}^{O_p} D^i_p(t).\beta_{opm}(t).t_{opm}(t)\ge q.$$
$$\left[\frac{1}{K}.\sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{p=1}^{P}\sum_{o=1}^{O_p} D^i_p(t).\beta_{opm}(t).t_{opm}(t)\right];\forall(k,t) \quad (21)$$

$$\sum_{k=1}^{K}\sum_{m\in m_p(o+1,p)} X_{o+1,pmk}(t)=\sum_{k=1}^{K}\sum_{m\in m_p(o+1,p)} X_{opmk}(t),\forall O\in O(p)/\{O_p\},$$
$$\forall p\in p,\forall t\in t \quad (22)$$

$$PA_m(t=1)=PA_m(t=0)+PN_m(t=1),\forall m \quad (23)$$

$$PA_m(t)=PA_m(t-1)+PN_m(t),\ \forall\, m,t \quad (24)$$

Where $PA_m(t)=\sum_{k=1}^{K}N_{mk}(t)$ & $PA_m(t-1)=\sum_{k=1}^{K}N_{mk}(t-1)$,

$$Y^{+}_{mk}(t),Y^{-}_{mk}(t),N_{mk}(t)\in\{0,1,2,.........;\}\ \&$$
$$\nu_{opk}(t),\mu_{mk}(t)\in\{0,1\};and..\text{int}\,eger,\forall(p,o,m,k,t)$$
$$X_{opmk}(t)\ge 0,and..\text{int}\,eger,\forall o,p,m,k,t$$
$$Q^H_p(t)\ge 0,and..\text{int}\,eger,\forall p,t$$
$$Q^o_p(t)\ge 0,and..\text{int}\,eger,\forall p,t$$
$$PN_m(t)\ge 0,and..\text{int}\,eger,\forall m,t$$
$$Z_{opmk}(t)\in\{0,1\}\forall o,p,m,k,t \quad (25)$$

The first term, first part of second term, second part of second term, third term, fourth term, first part of fifth term, second part of fifth term, sixth term, seventh term, eighth term, ninth term, tenth term, eleventh term of the objective function (3) represents machines procurement cost, machines maintenance overhead cost, machines breakdown repair cost ,part holding cost, machines setup cost, tool consumption cost, machines operation cost, production time loss cost of breakdown -machines, reconfiguration cost of machines installation, reconfiguration cost of machines removal, inter-cell move cost, outsourcing cost, intra-cell move cost, respectively. Constrains (4) and (5) show that the number of parts produced internally can be positive only if part *p* is produced internally by operation *o* on machine *m* in cell *k*, so that $z_{opmk}(t)=1$. Constraint (6) shows that demand of part *p*, $D_p(t)$ in each period *t* is satisfied through internal part production, $D^i_p(t)$ and/or part outsourcing $Q^o_p(t)$, and/or part inventory carried over from previous period *(t-1)*, $Q^H_p(t-1)$. Equation (7) shows that $\overline{\beta_p}(t)$ the proportion of total demand of part *p* to be outsourced in time period *t*. Equation (8) shows that $\beta_{opmk}(t)$, the proportion of total demand of part *p*, $D^i_p(t)$ the *o* operation on machine type *m* in cell *k* at time *t*. Constraint (9) shows that an assignment of an operation *o* of a part *p* is permitted only to a machine *m* having required tooling. This constraint is also for limiting the values of $\beta_{opmk}(t)$ within *[0, 1]*. The processing of an operation *o* of part *p* is allowed to be performed in at most $L_p(t)$ cells in time period *t* with constraint (10) & (11). Constraint (12) shows machine capacity constraint. Constraint (13) limits the number of type *m* machines to process at the beginning of period *t* to maximum possible. Constraint (14) is to ensure that the number of machines of type *m* in current period is equal to the number of machines in the previous period, adding the number of machines moved in and subtracting the number of machines moved out of the cell *k*. By constraint (15), lower and upper bounds on sizes of cell are enforced. Constraint (16) & (17) are for setting $\mu_{mk}(t)$ to 1 if at least one type *k* machine is located in cell *k* during period *t*, *0* otherwise. Constraint (18) is *o* ensure that machine pairs included in S^{dk} should not be placed in same cell. Constraint (19) is to ensure that machine pairs included in S^{sk} should be placed in the same cell *k*. Constraints (20) ensure values of $\beta_{opmk}(t)$, $\beta^H_p(t)$&$\overline{\beta}_p(t)$ in *[0, 1]* limit. Constraint (21) enforce workload balance among cells when the number of cells are *k*, the minimum allowable workload of cell is $((q/K)x100)\%$, of total workload in terms of processing time. The maximum allowable work load is given by $((q/K)+1-q)x100\%)$ of the total work load. When *q=1*, allowable work load is around average workload *(1/Kx100) %* of total work load. Constraint (23) is for material flow conservation in production. Constraint (24) relates to the machine availability $PA_m(t=1)$ constraint for period *t=1*, taking into consideration of the machines procured $PN_m(t=1)$. When $PA_m(t=0)=0${also $A_m(t=1)=0$} , it mean that there is no machine in system initially ; and a cm system is being designed and implemented from no existing manufacturing layout. If $A_m(t=1)>0$, there are machines already available in the system ; the existing manufacturing layout is being reconfigured to from CM layout . Constraint (25) relates to the machine available $PA_m(t)$ for the subsequent time period *t* *(t>1)*. It takes into account the extra machines procured $PN_m(t)$ in beginning of time period *t* and machine available $PA_m(t-1)$ in last period *(t-1)*. Objective function is a nonlinear integer equation due to the absolute ninth term & eleventh term. To transform ninth term & eleventh term of objective function into a linear term, non-negative variables $\phi^1_{opk}(t)$, $\phi^2_{opk}(t)$ &, $\mu^1_{opmk}(t)$, $\mu^2_{opmk}(t)$ are introduced, respectively . Terms are rewritten (7) by equation -26, 28. The constraints (27, 29) must be added to model.

$$\frac{1}{2}\sum_{t=1}^{T}\sum_{p=1}^{P}\sum_{o=1}^{O_p-1}\sum_{k=1}^{K}\left[\frac{D^i_p(t)}{B^{\text{inter}}_p}\right].\gamma^{iner}_p.(\phi^1_{opk}(t)+\phi^2_{opk}(t)) \qquad (26)$$

$$\frac{1}{2}\sum_{t=1}^{T}\sum_{p=1}^{P}\sum_{o=1}^{O_p-1}\sum_{k=1}^{K}\left[\frac{D^i_p(t)}{B^{\text{intra}}_p}\right].\gamma^{\text{intra}}_p.\left\{\sum_{\text{m}=1}^{M}\mu^1_{\text{opmk}}(t)+\mu^2_{\text{opmk}}(t)-(\phi^1_{opk}(t)+\phi^2_{opk}(t)\right\} \qquad (28)$$

$$(\phi^1_{opk}(t)-\phi^2_{opk}(t)=\sum_{m=1}^{M}\beta_{(o+1),pmk}(t)-\sum_{m=1}^{M}\beta_{opmk}(t) \qquad (27)$$

$$\mu^1_{\text{opmk}}(t)-\mu^2_{\text{opmk}}(t)=\beta_{(o+1),pmk}(t)-\beta_{opmk}(t),\forall o,p,m,k,t \qquad (29)$$

3. HYBRID HIERARCHICAL GENETIC ALGORITHM

A hybrid hierarchical genetic algorithm (HHGA) is developed to incorporate the design of solution representation, fitness evaluation of the solution, genetic operators and adaptive local search scheme specific to the model presented in the previous section.

3.1 Hybrid Genetic Algorithm

It has been known that most of the HGAs have better performance than GA, since the formers can overcome the weaknesses of GA such as the premature convergence of solution due to complex search spaces and constraints. One of the common types of hybridized GA is to include a local search technique the iterative hill climbing method by Young Su Y [21] to GA loop. The fitness function value ratio, *FFVR* (t) for the next generation is calculated as ratio of $F^{new-pop(t)}_{fit}$ to $F^{new-pop(t-1)}_{fit}$ .These are average fitness values of the new population resulting from roulette wheel selection strategy using parent and offspring populations at generation t & (t-1), respectively. With minimization of objective function, the adapting strategy (Fig-3), is to use the iterative hill climbing method to GA loop, if *FFVR (t)>1*; otherwise use GA only.

Iterative hill climbing method in GA loop

begin

select an optimal individual vc in current GA loop; randomly generate as many individuals as the population size in the neighborhood of V_p and then calculate the fitness values of the generated new individuals using the objective function F_{fit}; select the individual Vn with the optimal value among the fitness ones of the new individuals;

if F_{fit} (V_p) > F_{fit} (Vn) **then** V_p ←Vn **end**

end

3.2 Hierarchical scheme for chromosomal encoding & decoding of a solution

Figure1 describes a hierarchical scheme of chromosome representation of a solution of problem-1 with 8 parts, 6 machines and three periods. These parts with zero demand are not includes in the chromosomes structure. Figure 2 shows details of coding scheme of a part p6. In Figure 2, part *p6=6* coding scheme has three operations $O_p = 1,2,3$ with two alternative *n=1,2* routings each, part holding fraction $\beta_p^H(t)$, cell for operation O_p execution c_{pok}, outsourcing fraction $\overline{\beta_p}(t)$ & alternate route-operation lot splitting fraction $\beta_{opm^n{}_k}(t)$ for operation O_p with *'n=1,2,'* routings $\{K^1, K^2, \dots\dots\dots, K^n\}$. c_{pok} takes a value *{1,2,…..,K}* *,K=2*. $\beta_p^H(t)$,$\overline{\beta_p}(t)$ & $\beta_{opm^n{}_k}(t)$ has a value in range *[0, 1]*. It is used to computes the proportions of production volume among alternate routings. Operation that do not have alternative routings, do not have $\beta_{opm^n{}_k}(t)$. The decision variables $\beta_p^H(t)$, $\overline{\beta_p}$ (t) & $\beta_{opmk}(t)$ are found directly by decoding a chromosome under consideration. The values $\beta_{opm^1{}_k}(t), \beta_{opm^2{}_k}(t), \dots\dots, \beta_{opm^n{}_k}(t)$ are found using sets of equations – 6, 7,8,30. The corresponding integer variables $N_{mk}(t), y^+_{mk}(t)$ & $y^-_{mk}(t)$are found using a problem specific heuristic [12]. The chromosomal coding scheme satisfies constraints 4, 5, 6, 9, 10,11,23,25.

$$\beta_{opm^1{}_k}(t) + \beta_{opm^2{}_k}(t) + \dots + \beta_{opm^n{}_k}(t) = 1 \tag{30}$$

3.3 Genetic Operators

Roulette wheel selection operator with single point standard crossover operator is used. We used seven different mutation operators. Mutation operator are the part inventory held mutator, the outsourcing mutator , the operation-In- cell mutator, the alternative route-operation lot splitting fraction mutator. The part inventory held degenerator the outsourcing degenerator, and the alternative route-operation fraction degenerator. The part inventory held mutator (PIHM) & part outsourcing mutator (POM) randomly steps up or down the variable $\beta_p^H(t)$ & $\overline{\beta_p}(t)$ by a certain step value. This operator also takes care of the constraint in equation (17, 18) of the model. The operation-In- cell mutator (OICM) changes the value of the c_{pok}'s. This operator is applied for each operation independently. It may result in different values of c_{pok} for the operations of a part. The alternative route-operation lot splitting fraction mutator (AROM)randomly steps up or down the variable $\beta_{opm^n{}_k}(t)$ for all the operations having alternative routings by a certain step value while keeping these values in [0,1]. Since $\overline{\beta_p}(t)$i and$\beta_{opm^n{}_k}(t)$ are kept in [0, 1], ensures the constraint in equation (16) of the model. All the mutation operators discussed above are applied with small probabilities.

The part inventory held degenerator (PIHD), the outsourcing degenerator (POD) and alternative route-operation fraction degenerator(AROD) are non-probabilistic mutation operators. The part inventory held degenerator sets the value of $\overline{\beta_p}(t)$ =0 if its current value is less than a degeneration limit, *d1*. It also sets $\overline{\beta_p}(t) = 1$ if its current value is greater than (1 - *d1*). The outsourcing degenerator sets the value of $\overline{\beta_p}(t) = 0$ if its current value is less than a degeneration limit, d2. It also sets $\overline{\beta_p}(t) = 1$ if its current value is greater than (1-d2). The alternative routing-operation fraction degenerator sets a value of $\beta_{opm^n{}_k}(t) = 0 \ or \ 1$ based on the magnitude of flow along the alternative routes of an operation. For an operation o of part p with two alternative routings, the operator sets $\beta_{opm^1{}_k}(t) = 0$ if its current value is less than a degeneration limit, d3. It also sets $\beta_{opm^1{}_k}(t) = 1$ if its current value is greater than (1 - d3). These three operators are aimed to speed up convergence by quickly degeneration of insignificantly small values of the continuous decision variables.

Table III: Test data for experiment-1 part, machines, operations, routes & alternative routings, tool no. ,operation time ,setup time ,demand in periods, process batch sizes (Bs),inter-cell transfer batch sizes (Teb) ,intra-cell transfer batch sizes(Tab), Tool indices, inter-cell move cost, intra-cell move cost.

Part (p	→	P1			P2			P3			P4			P5			P6			P7			P8		
Operation	Op	op1	op2	op3	op1	op2	op3	op1	op2	op3	op1	op2	op3	op1	op2	op3	op1	op2	op3	op1	op2	op3	op1	op2	Op3
M/C(m)	TNO												13					3							17
M1	OT(min)												45.6					34.2							32.4
	ST(hr.)												12					9.0							9.0
M2	TNO	1	10		3	9	4		11		4	8		6			5		9	8		11		6	
	OT	40.8	36.6		40.2	13.8	14.4		11.4		33	34.8		42.6			43.2		28.2	26.4		16.8		10.2	
	ST	11	10		11	4	4.5		3.2		9.0	9.0		10.5			10.5		9.0	7.0		4.5		3.2	
M3	TNO		10	16		9	14				4										2				17
	OT		37.8	52.8		28.8	34.2				49.2										58.2				9
	ST		10.5	13.5		8.0	9.0				12.0										15				3.0
M4	TNO			16				2		15					7						2		7	6	
	OT			37.8				7.8		34.8					29.4						28.2		50.4	8.6	
	ST			10.2				3.0		9.2					7.5						7.5		13	13	
M5	TNO	1			3				11	15			13	6		12			9	8		11	7		
	OT	33			47.4				53.4	56.4			15.6	10.2		39			7.2	45.6		51.6	12		
	ST	9			12				13.5	15			4.5	3.5		10.0			2.5	12		10.5	3.5		
M6	TNO							2				8			7	12	5	3							
	OT							21.6				46.8			27	35.4	48.6	28.8							
	ST	+						6				12			9.0	9.2	12	7.5		110					
Demand	PR1	250			0			0			725			385			660			610			670		
	PR2	535			495			0			625			0			550			220			495		
	PR3	750			0			660			0			825			445			390			450		
Tab		5			5			4			7			4			8			8			6		
Teb		25			25			20			35			20			40			40			30		
Bs		100			125			150			125			175			125			150			125		
Tool Indices	Op1	1			3			2			4			6			5			8			7		
	Op2	10			9			11			8			7			3			2			6		
	Op3	16			14			15			13			12			9			11			17		
inter-cell cost$		24			27			18			21			23			20			25			17		
intra-cell cost$		5			6			4			4.5			5			4			5			3.5		
Holding cost$		2.7			2.6			2.5			2.6			2.7			2.7			2.7			2.6		

Constraints are managed in equations (14) and (19) by the penalty method; in equations (15, 16, 17, 18, 25) by Repair Scheme; manages constraints in equations (12, 13, 14, 23, 24, and 25) by Machine Allocation Scheme; in equations (18) by genetic operators. Due to page limit of journal, we are not able to describe in detail about the fitness function, Repair Scheme & Machine Allocation Scheme design .These are almost similar as authors [12] GA. Readers are advised to read papers HGA [21] & GA [12].

Table IV: Machines, Available tool indices, Amortization cost, M/c Relocation costs- Addition/ Removal, Time capacity, Breakdown cost, Maintenance overhead costs, MTBF(m), MTTR(m).

M/C m	Avlaible Tool Indices	Amor. cost $	Relocation cost $		Time cap. hrs.	B.down cost $	Maint.o heads $	MT BF(m) hrs	MTTR (m) hrs
			Add.	Rem.					
M1	3,13,17	1300	625	605	600	1200	390	90	3
M2	1,3,4,5,6,8,9,10,11	1500	720	695	600	2500	450	51	8
M3	2,4,9,10,14,16,17	1600	790	740	600	2225	480	73	6
M4	2,6,7,15,16	1500	730	705	600	1800	450	60	7
M5	1,3,6,7,8,9,11,12,13,15	1300	640	550	600	2100	390	76	2
M6	2,3,7,8	1600	830	805	600	2300	480	62	4

Table V: Other parameters values for experiment-1.

S.No.	Parameters	Parameter values
1	No. of cells	2
2	Upper bound for cell size for machines	10
3	Lower bound for cell size for machines	2
4	Pair of machine should be in different cells	{ (M2,M6);(M3,M4) }
5	Pair of machine should be in same cells	{ (M1,M5);(M2,M5)}
6	Workload balancing factor ,q	0.9

← *NA-No solution Available,*
← *NT-No Termination criteria Meet*

Table VI: Cell formation for period -1,2,3.

Cell formation for Period- 1							
Parts m/c No.	M2	M5	M4	M1	M5	M2	M3
Qty.	3	1	1	1	1	1	1
P4	1,2 (.661)	3 (.331)					
P6	1 (1)			2 (1)	3 (1)		
P7	1 (1)		2 (1)			3 (1)	
P5		1,3 (1)	2 (1)				
P'4					3 (.339)	1,2 (.339)	
P1					1 (1)	2 (1)	3 (1)
P8					1 (1)	2 (1)	3 (1)

Cell formation for Period- 2							
Part M/c No.	M2	M5	M4	M1	M5	M2	M3
Qty	3	1	1	1	1	1	1
P2	2,3 (.446)	1 (.446)					
P4	1,2 (.558)	3 (.558)					
P7	1,3 (1)		2 (1)				
P'1		1 (.61)	2,3 (.61)				
P1					1(.39)		2,3 (.39)
P'2						2,3 (.554)	1 (.554)
P6				2 (1)	3 (1)	1 (1)	
P4'					1 (.452)	2,3 (.452)	
P8					1 (1)	2 (1)	3 (1)

Cell formation for Period- 3						
Part M/c No.	M2	M4	M1	M5	M2	M4
Qty.	2	2	1	1	1	1
P1	1,2 (1)	3 (1)				
P3	2 (.82)	1,3 (.82)				
P7	1,3 (.89)	2 (.89)				
P5				1,3 (1)		2(1)
P6			2 (1)	3 (1)	1 (1)	
P8			3 (1)	1 (1)	2 (1)	
P3'				2 (1)	2 (.18)	1,3 (.18)
P7'					1,3 (.11)	2 (.11)

Table VII: Cell loads for Period- 1, Period- 2, Period- 3,q=0.9 & q=1.

Period →		Period 1 Min.	Period 2 Min.	Period 3 Min.
Cell 1		1975	1620	1884
Cell 2		1968	1654	1923
Average cell load		1971.5	1637	1903.5
q=0.9	Minimum load	1774.5	1473.33	1713.15
	Maximum load	2168.65	1800.7	2093.85
q=1	Near Allowable load	1971.5	1637	1903.5

Table VIII: HHGA comparison with LINGO.

Time	Objective (lakhs)$	
(h:min:s)	LINGO	HHGA
00:00:04	NA	1.27358
00:00:09	NA	1.26536
00:00:11	NA	1.25314
00:00:15	NA	1.24763
00:00:23	NA	1.22137
00:00:34	NA	1.21862
00:00:50	NA	1.19239
00:01:07	NA	1.17624
00:02:14	NA	1.16872
00:03:25	NA	1.15328
00:04:29	NA	1.13644
00:05:36	1.25053	1.13409
00:05:55	1.25093	1.13238
00:07:84	1.24084	1.13116
00:08:56	1.23079	1.13116
00:10:05	1.21310	1.13032
00:11:12	1.19067	1.13031
00:16:48	1.17021	1.12957
00:33:36	1.16045	1.12957
01:07:00	1.15023	NT
01:47:00	1.13344	NT
02:48:00	1.13344	NT
05:36:00	1.13344	NT

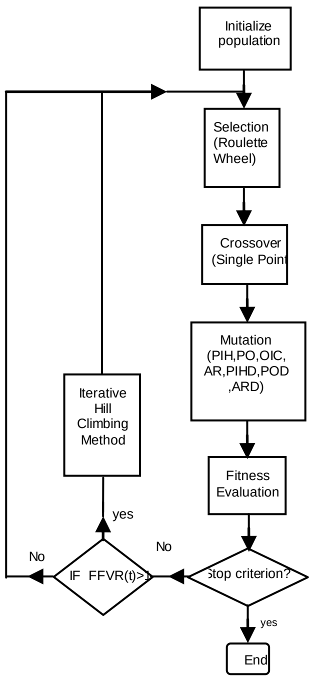

Figure 3: Flow chart of hybrid hierarchical adaptive genetic algorithm.

Table IX: Data for experiments no. 2 to 6.

S. No.	Experiment No. → Factors ↓	Source→	Exp-2	Exp-3	Exp-4	Exp-5	Exp-6
			Chen & Cao (2004)	Chen & Cao (2004)	Nsakanda et al. (2006)	Defersha and chen (2006)	Nsakanda et al. (2006)
1	No. of part types		4	5	15	25	20
2	No. of operations per part		2-3	2-4	2-3	4-9	2-9
3	No. of machine types		4	5	15	10	20
4	No. of cells		2	4	3	5	5
5	No. of time periods		3	6	1	2	1

4. COMPUTATIONAL EXPERIMENTS AND RESULTS

Here, we show our computational experience on the proposed model. The test problems are solved on a PC with Intel core duo two, 4GB RAM. The model proposed in this paper considers a larger coverage of the attributes than the individual papers by other authors. The unknown input parameters were generated by cross-referencing between data sets possessing them and then included within other data sets that are missing this information. Hence, all data sets employed in each solved example posses' values within the same range. For example, MTBF & MTTR values in problems are used in approximation from Ameli et al [9]. We used the real-life data collected from a company running in a CMS environment in terms of number of part types, machine types, operation and number of cells in Table-IX. It causes difficulty in solving these problems in terms of computational time. Hence, the variables which can be made zero, can be removed from model. The variable with zero values are removed from model using sparse set membership filtering technique of LINGO. After these variables are made zero, some of constraints becomes redundant. These constraints were also removed from the model.

This example is described in detail for its input data and computational results. Here, we consider *6* different types of machines, *8* different part types, and *3* planning periods with potentially non-zero 4217 variables and 4368 constraints. The input data of this example are given Tables-III to Table-V. The values of HHGA parameters are 360,.4,.005,.00 5,.0005,.06,.06.0.6,.2,.2,.06 for population size, probabilities of single point crossover mutator , probabilities of the part inventory held mutator, the outsourcing mutator , the operation-In- cell mutator, the alternative route-operation lot splitting fraction mutator, degenrator limit *d1*, degenrator limit *d2*, degenrator limit *d3*,step amount for part inventory held mutator, the outsourcing mutator , the alternative route-operation lot splitting fraction mutator, respectively. Cells generated in Time period-1, 2, 3 & work load of cells are given in Table-VI. In period 1, Part *P4* is processed with lot splitting 0.661 for operation 1 &2 on machine *M2* in cell-1 & so on. Part *P1 & P8* are processed in cell-2 without lot splitting. In period 2, there is removal of one unit of machine *M2* from cell-1 due to reconfiguration & so on. For part *P3*, in time period-1, outsourced zero, internal production 50 for parts holding for period-3 although demand is zero in time period-2 & so on. Work load is presented in Table-VII. It is obvious that work loads are near average cell load. Workloads are also within minimum & maximum workloads limits. In other words, cells have balanced workloads. Grand total cost is found $113,344 in 1 hrs. and 47 min. with LINGO & in 5 min. and 36 sec with HHGA. Table-VIII shows objective value comparison between LINGO & HHGA.

It is natural that with increase in size, computational time/ increases. Problem-2, Chen & Cao [19] was solved in time 1 hour and 6 min., optimality gap .0072, with potentially non-zero 3219 variables and 3362 constraints with LINGO & in 5.04 min. with HHGA. Problem-3, Chen & Cao [19] was solved in time 1 hrs and 19 min., optimality gap. 0072 with potentially non-zero variables 4184 and 4368, constraints with LINGO & in 5.34 min. with HHGA. Problem-4, Nsakanda et al. [15] was solved in time 1 hrs and 30.4 min., optimality gap .0076, with potentially non-zero variables 4506 and 4714 constraints with LINGO & in 6.48min. with HHGA. Problem-5, Defersha and Chen [12] was solved in time 2 hrs. & 44.8 min. Optimality gap .0076, with potentially non-zero variables 8369 and 8740 constraints with LINGO & in 12.28 min. with HHGA. Problem-6, Nsakanda et al. [15] was solved in time 3 hrs. & 13.6 min., optimality gap .016, with potentially non-zero variables 9978 and 10421 constraints with LINGO & in 15.01 min. with HHGA. Problem-7, Nsakanda et al. [15] was solved in time 5 hrs. & 12 min., optimality gap .029, with potentially non-zero variables 17604 and 18304 constraints with LINGO & in 24.11 min. with HHGA. Problem-8, [15] was solved in time 6 hrs. & 0.2 min., optimality gap 26.41, with potentially non-zero variables 35413 and 30367 constraints with LINGO & in 35.19 min. with HHGA.

5. CONCLUSION

We presented a DCMS model integrating breakdown effects, production planning, dynamic system reconfiguration intracellular movement, transfer batch sizes and several other attributes. We also designed a hybrid hierarchical genetic algorithm to solve the model. Some computational experiments also performed with model HHGA. Our experience shows that HHGA needs much less computational time than LINGO-based approach. Further, we intend to enhance the model with attributes such as production control, selection of material handling equipment and equipment layout etc.

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A COMPARATIVE STUDY OF METHODS FOR MANUFACTURING PROCESS PLAN SIMULATION

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Abstract:
In order to optimize the manufacturing costs of mechanical parts, tolerance synthesis within computer aided design and manufacture systems has to be built on appropriate methods that can integrate both quality and cost. With this aim a comparative study between three widely used methods of manufacturing process plan simulation is performed. The first method is the vector chain method usually used in the design tolerance analysis procedures. The second one is the dispersions method that uses the manufacturing capability parameters. The third one is the statistical modelling based method. Firstly, a graphical representation of the acceptance zones of the parts for each method is used. Then, the impact of writing conventions of the functional requirement (minimal, middle or maximal tolerance zone) on the vector chain simulation method is highlighted in comparison to the other two methods. Lastly, an analysis of the effect of the three methods of simulation on the formation of the acceptance zones of the parts for a manufacturing process is conducted. This analysis has clearly showed that the dispersions method is very effective and very sure in the simulation of the manufacturing process plan. The non rational vectorial method largely used in industry can reject parts during the manufacturing process, although the rejected parts could be accepted in the final control stage of the functional requirements. On the other hand the statistical modelling gives wider manufacturing tolerances. However, this method presents a reject risk. In this case a very rigorous control strategy in the production line should be implemented. Consequently this paper presents assistance to manufacturing engineers in order to choose the appropriate simulation method to verify the manufacturing process plan.

Key Words: Manufacturing tolerances, Simulation, Dispersions, Statistical tolerancing, Acceptance zones

1. INTRODUCTION

For several years during process plan simulation of manufacturing process plan, process engineers have been able to choose between several methods of tolerancing. The non-rational vector chain method and the dispersions or ∆l method introduced by Bourdet [1], [2] are among the most frequently used with a strong prevalence of the first method. The strong implementation of the vector chain method in industry is the result of the training actions in process plan simulation as well as in engineering design department during the calculation of the resulting clearances. In spite of the of vulgarisation efforts developed since thirty years to support the implementation of the ∆l method in industrial areas, it remains difficult to introduce new manufacturing simulation practices in the industrial environment. The principal obstacle is the need to integrate the adjustment process of the means of production in the simulation of the manufacturing process plan. However, by confusing the adjustment process and the manufacturing process, the users impose new constraints on the production by adding useless tolerance transfers.

It is very significant to recall that the ∆l method makes it possible to obtain in certain cases acceptance zones 1.5 wider than those provided by the vector chain method [3]. The use of statistical models [4], [5] permits to obtain acceptance zones for parts even wider than those given by the two previous methods of simulation.

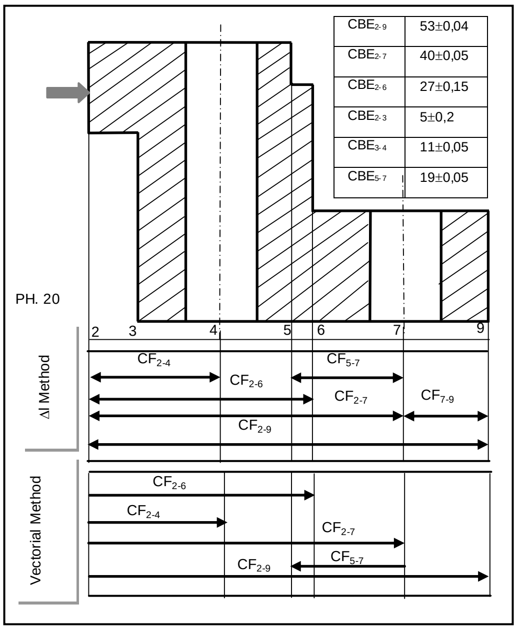

Figure 1: Intermediate geometry of phase 20.

This paper presents a comparative study of the acceptance zones obtained by the vector chain method, the ∆l method and the statistical modelling based method. In order to illustrate the study, the example defined by Figure 1 is used. In this example, the intermediate geometry (production drawing) of phase 20 of the process plan and the functional dimensions (CBE) to be machined, are presented.

2. ACCEPTANCE ZONE BY THE ∆L METHOD SIMULATION

The drawing of Figure 1 shows the presence of a dimension chain. In this case, the manufacturing dimensions $CF_{2\text{-}9}$, $CF_{2\text{-}7}$ and $CF_{7\text{-}9}$ are independent between them since they do not take part in the realization of the same design functional dimension. This is translated graphically by an acceptance zone called also zone of production as is illustrated in Figure 3 [6].

To illustrate the acceptance zones formed by the calculated dimensions CF, a well-known property which makes it possible to represent the sum of all the points (a_i, b_i) by a direct line with the slope coefficient (-1) is used (see Figure 2).

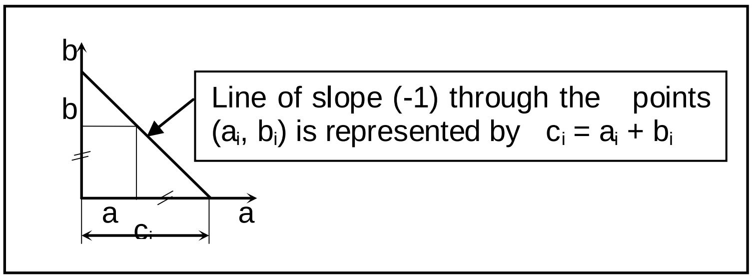

Figure 2: Artifice of representation.

When applied to dimension CF_{2-9} which is the result of an addition between CF_{2-7} and CF_{7-9} in phase 20 of figure 1, the acceptance zone of the parts is given by the shaded area as shown in Figure 3. All the parts, whose dimensions are inside this zone, conform to the conditions of both design and manufacturing dimensions.

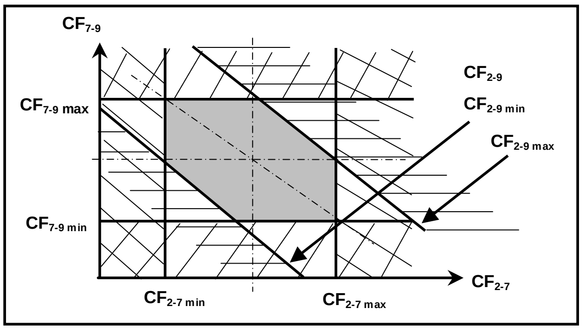

Figure 3: Acceptance zone by ∆l method simulation.

3. ACCEPTANCE ZONE BY THE VECTOR CHAIN METHOD SIMULATION

This method applies the philosophy of the adjusting operator who imposes (n-1) dimensions. If we wish to impose only two CF on the closed chain of Figure 1, then, there is reduction in the zone of production since there will be transfer of one of the three CF. For example, we wish to keep the dimensions CF_{2-9} and CF_{2-7}. By using the rules of dimensions transfer, the tolerance interval of dimensions CF_{2-9} and CF_{2-7} take the value of 0,025 mm in order to satisfy the tolerance of dimension CF_{7-9} whose value is equal to 0,05. This example explicitly shows the mechanism of reduction of the tolerance interval (IT) which occurs when the non-rational vector chain method is employed.

The zone of acceptance of the parts manufactured by the vector chain method can be visualized according to the type of convention: maximal condition, minimal condition or mean condition. Figure 4 shows the dimensions CF_{2-9} and CF_{2-7} obtained according to the mean condition convention. They are of an interest for the illustration of the acceptance zone by the vector chain method. In order to compare the results of the two methods, the acceptance zone of the vector chain method is mapped in black on the same graph. According to simulation by the ∆l method, all the parts belonging to the grey shaded zone, conform to the conditions of both design and manufacturing dimensions. Those belonging to the black zone conform to the same conditions in accordance with the simulation by the vector chain method. A coefficient of reduction for accepted parts of 2/3 of is registered.

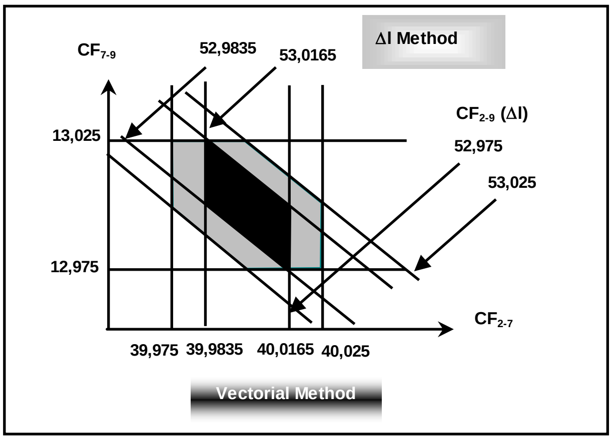

Figure 4: Acceptance zone by vectorial chain method simulation in mean convention.

For the case of maximal convention, the acceptance zone is located to the right limit of the grey zone, while that carried out in minimal convention is shifted on the left grey zone as shown in Figure 5.

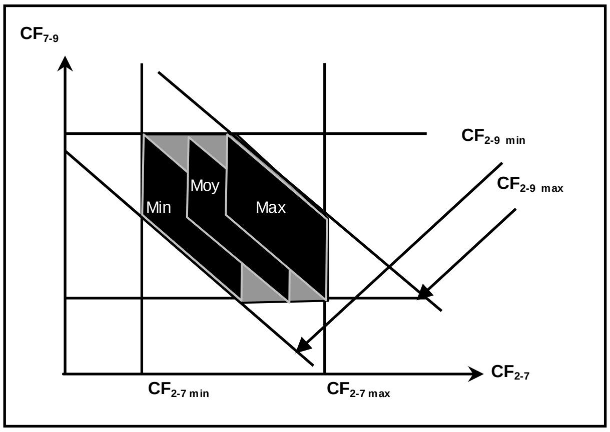

Figure 5: Acceptance zones by vectorial chain method simulation in minimal, maximal and mean convention.

The ΔI based rational methods give an acceptance zone wider than that given by the non-rational vector chain method. The vector chain method over constrains the tolerances of the dimensions CF. This is due to the introduction of the adjustment process. The manufacturing dimensions obtained by the ΔI method gives a greater freedom of manufacture and, thereafter, a reduction in the manufacturing costs.

4. WEIGHT OF CONVENTION ON ACCEPTANCE ZONES OF PARTS

For better visualizing, the weight of each convention on different simulations of the manufacturing process plan, a representation of acceptance zones of the two methods on the same graph is needed (Figure 6).

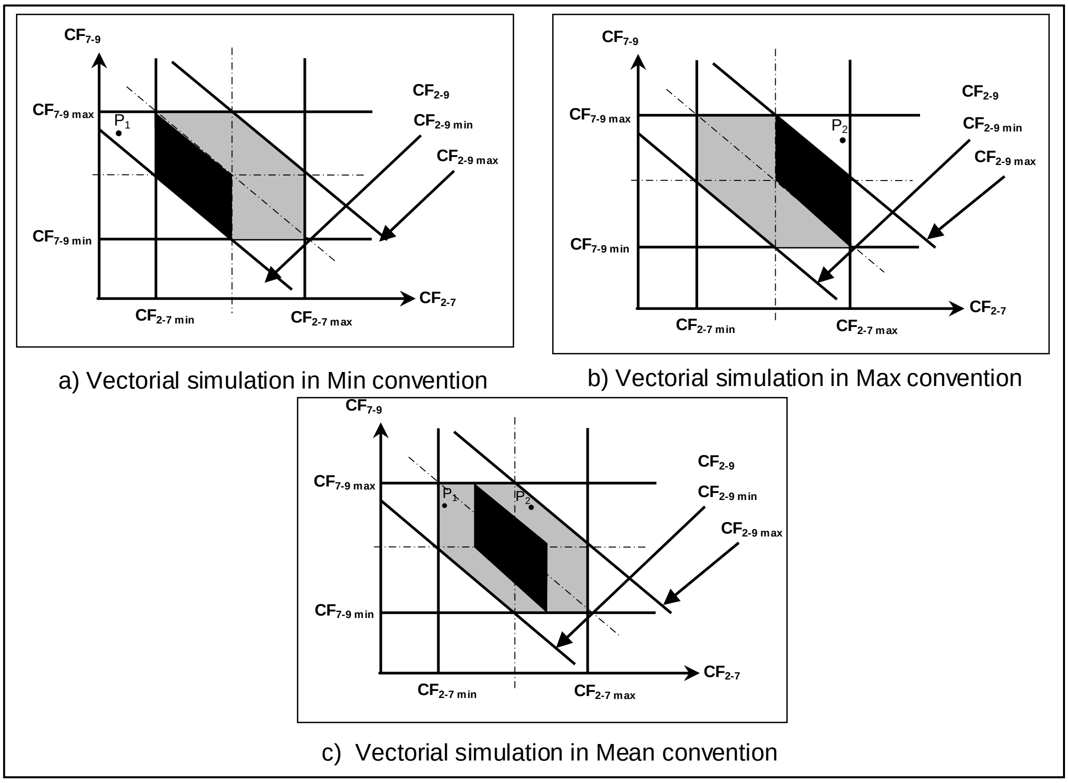

Figure 6: Vectorial simulation of the pre-projects by the three conventions.

For a series of simulated parts by both vector chain method in minimal convention and ∆l method, the results are given in Figure 6. For the two cases, the part P_1 located to the left limit of the acceptance zones is not accepted as figure 6a shows.

In the same way, for the simulation by both ∆l and vector chain method in maximal convention, the results are illustrated by the graph of Figure 6b.

The part P_2 located to the right limit of the acceptance zones is not accepted in the case of simulation by the two methods.

The simulation of the same series of parts by the ∆l method and the vector chain method in mean convention gives the graphical results illustrated by Figure 6c. The use of mean convention tries to recover parts (P_1, P_2) having the same defects, by using the wider zone given by the ∆l method and applying workshop adjustments during manufacturing.

Consequently, if we are constrained to simulate manufacturing process plan by the vector chain method for a reason or for another, it is preferable to simulate the pre- project in mean condition convention [7].

5. ACCEPTANCE ZONE BY STATISTICAL MODELLING SIMULATION

In order to perform an optimized tolerance distribution, a statistical and cost based optimization model has been developed in a previous work [8]. This model takes into account the stochastic aspects of the machining dispersions as well as the complexity and cost of manufacturing the dimensions. The model uses a cost-tolerance database [9] built as shown in Figure 7. The final synthesis model for the manufacturing tolerances is expressed as follows:

minimising:

$$C_{PP} = \sum_{j=1}^{p} \sum_{i=1}^{n_j - m_j} \sum_{k=1}^{l} \left(\frac{C_{jik} - C_{jik-1}}{T_{CFjik}{}^2 - T_{CFjik-1}{}^2} \right) . X_{jik} + \sum_{t=1}^{m} \sum_{k=1}^{l} \left(\frac{C_{tk} - C_{tk-1}}{T_{CFctk}{}^2 - T_{CFctk-1}{}^2} \right) . X_{tk} \quad (1)$$

with the constraints:

$$T_{CCj}{}^2 \geq \sum_{i=1}^{n_j - m_j} T_{CFji0}{}^2 + \sum_{t=1}^{m_j} T_{CFct0}{}^2 + \sum_{i=1}^{n_j - m_j} \sum_{k=1}^{l} X_{jik} + \sum_{t=1}^{m_j} \sum_{k=1}^{l} X_{tk} \qquad \forall j \quad (2)$$

$$0 \leq X_{jik} \leq [T_{CFjik}{}^2 - T_{CFjik-1}{}^2] \qquad \forall j,i,k \quad (3)$$

$$0 \leq X_{tk} \leq [T_{CFctk}{}^2 - T_{CFctk-1}{}^2] \qquad \forall t,k \quad (4)$$

$$T_{CFjik}{}^2 = T_{CFji0}{}^2 + \sum_{k=1}^{l} X_{jik} \qquad \forall j,I \quad (5)$$

$$T_{CFctk}{}^2 = T_{CFct0}{}^2 + \sum_{k=1}^{l} X_{tk} \, \forall t \quad (6)$$

This manufacturing tolerance synthesis model is built as a linear programming (LP) problem. The Simplex technique is used to solve the LP problem. The computed unit tolerance variables X are then used to calculate the manufacturing tolerances T_{CF}.

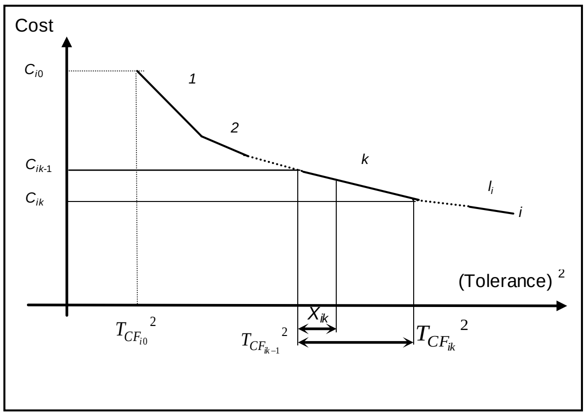

Figure 7: Cost-tolerance database.

The best way to highlight the advantages of using statistical modelling is to represent dimensions CF_{2-9}, CF_{2-7} and CF_{7-9} of section 2 obtained by using the statistical based tolerance synthesis model developed.

The dimension CF_{2-9} is the result of an addition between CF_{2-7} and CF_{7-9} in phase 20 of figure 1. The zone of acceptance of the parts by statistical modelling is shown by the hatched zone on Figure 8. This zone is wider than that obtained by the worst case based ∆l method or vectorial method.

Statistical modelling gives a wider tolerance interval than the two previous methods. This increase in the tolerance interval allows the use of less precise manufacturing equipment, thus less expensive.

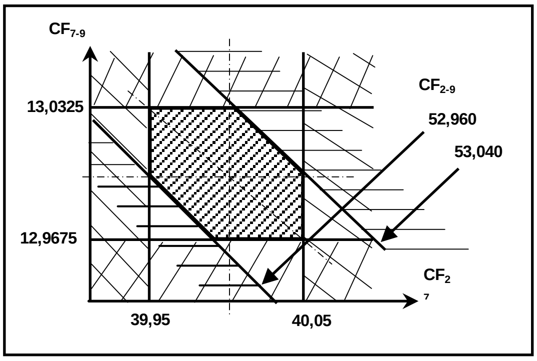

Figure 8: Zone of acceptance given by statistical modelling.

To quantify this impact, Table I presents a comparison of the unit manufacturing costs for the three methods. This table shows that the ∆l method based simulation gives a cost reduction of 40,09% in comparison to the vectorial method based simulation. These two methods are both based on the worst case principle of calculation which means that a 100% of the parts are accepted. This fact qualifies the ∆l method as a very effective and very sure method for simulating the manufacturing process plan.

In addition, the table shows a very high cost reduction for the statistical modelling based simulation (66,97% compared to the vectorial method and 43,76% compared to the ∆l method). These results give a clear idea on the importance of the application of statistical tolerancing in the industrial field. These facts are represented in terms of acceptance zones for the three methods in Figure 9.

This figure shows that the zone of acceptance by statistical modelling in hatched is wider than that obtained by the ∆l method in grey and vectorial in black. These two last methods use the worst case tolerance synthesis principle.

Table I: Comparative table of unit costs by the three methods of simulation.

	VECTORIAL METHOD		∆L METHOD		STATISTICAL MODELLING	
Dimension	Tolerance [mm]	Cost [unit]	Tolerance [mm]	Cost [unit]	Tolerance [mm]	Cost [unit]
CF_{2-7}	0,033	2,913	0,05	1,745	0,1	0,920
CF_{2-9}	0,033	2,913	0,05	1,745	0,08	1,004
CF_{7-9}	-	-	0,05	1,745	0,065	1,02
1st total Cost	-	5,826	-	3,490	-	1,924
Cost reduction towards Vectorial Method	-	-	-	**40,09%**	-	**66,97%**
2nd total Cost	-	-	-	5,235	-	2,944
Cost reduction towards ∆l Method	-	-	-	-	-	**43,76%**

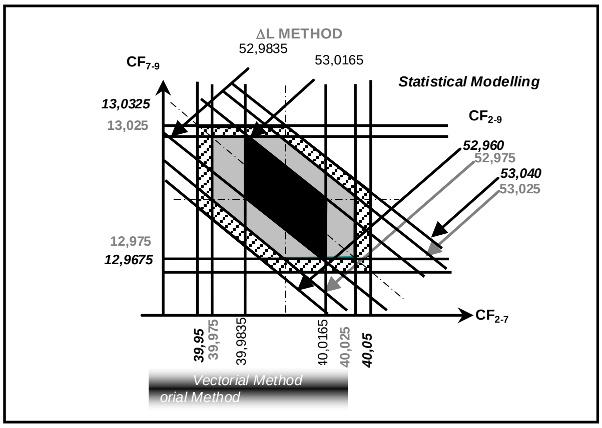

Figure 9: Acceptance Zones of the three simulation methods.

6. CONCLUSION

This study showed that the ∆l method which is based on the worst case principle is very effective and very sure in the simulation of the manufacturing process plan. Its effectiveness largely exceeds the non rational vectorial method largely used in industry. This last method can reject parts during the stage of manufacturing whereas they would be accepted in the final control stage of the functional requirements. The parts exceeding the limits imposed by the vectorial method are acceptable by the ∆l method. On the other hand the vectorial simulation in mean convention gives an acceptance zone centred in the middle of that of the ∆l method. This permits the acceptance of scrapped parts by the minimal and maximal convention simulation. In addition the statistical modelling based simulation gives definitely better results than those given by the two other methods if they use an optimization in the worst case. It increases the manufacturing acceptance zones compared to the two other methods. However, its use presents a reject risk of about 2,7‰ parts for only one dimension corresponding to the 99,73% (6σ) confidence level. It should however be thought that for a part having 10 dimensions, its probability of being scrapped will be of 2,6%. This remark imposes the implementation of a very rigorous control strategy in the production line.

NOMENCLATURE

σ standard deviation for a manufacturing dimension
Δ*l* dispersion of a machined surface or a positioning surface
i index for a manufacturing dimension
j dimension chain or tolerance chain
k linear segment in the tolerance-cost curve for a dimension
l number of segments in the tolerance-cost curve for a dimension
m number of common tolerance components in the process plan
n number of tolerance components in the tolerance chain
p number of design dimensions or manufacturing tolerance chains
t common manufacturing dimension
C cost factor of tolerance
T tolerance
X linear unit tolerance segment variable
P_1, P_2 Parts
CC design dimension condition
CF manufacturing dimension
PP process plan

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APPLICATION OF GREY BASED TAGUCHI METHOD IN MULTI-RESPONSE OPTIMIZATION OF TURNING PROCESS

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Abstract:
Metal cutting is one of the most significant manufacturing process in material removal and turning is the most commonly used method for metal cutting. This paper presents the multi-response optimization of CNC turning parameters using grey based Taguchi method. Experiments are designed and conducted based on Taguchi's L_{27} orthogonal array design. The turning parameters are cutting speed, feedrate, depth of cut and nose radius and the responses are surface roughness and power consumption. Taguchi's signal-to-noise (S/N) ratio are determined based on their performance characteristics. A grey relation grade is obtained by using S/N ratio. Based on grey relational grade value, optimum levels of parameters have been identified by using response table and response graph and the significant contributions of controlling parameters are estimated using analysis of variances (ANOVA). Confirmation test is conducted for the optimal machining parameters to validate the test result. The proposed method is having prediction accuracy and competency. This method may be extended to other machining processes.

Key Words: Power Consumption, Surface Roughness, Multi - Response Optimization, Orthogonal Array, Grey Based Taguchi Method, ANOVA, Turning Process

1. INTRODUCTION

Metal cutting is one of the most significant manufacturing processes in material removal and turning is the most commonly used method for metal cutting. Turning operations are evaluated based on the performance characteristics such as surface roughness, material removal rate (MRR), tool wear, tool life, cutting force and power consumption. These performance characteristics are strongly correlated with cutting parameters such as cutting speed, feed rate, depth of cut, and tool geometry. It is an important task to select cutting parameters for achieving high cutting performance [1, 2]. There is a need to operate these machines as efficiently as possible in order to obtain the required payback [3]. Achieving desired surface quality is of great importance for the functional behaviour of the mechanical parts [4]. With the recent increase in energy demand and constraints in the supply of energy has become a priority for the manufacturing industry. Very few research attempts have been done to estimate the significance of energy required and its cost for the CNC machining process as an integral part of the optimization process. In today's manufacturing industry, special attention is given to surface finish and power consumption. Traditionally the desired cutting parameters are determined based on experience and handbooks [5]. This method is limited in applications.

Optimization problems are solved by conventional and non-conventional optimization techniques [6]. Conventional techniques may be broadly classified into two categories: In the first category, experimental techniques that include statistical design of experiment, such as Taguchi method, and response surface design methodology. In the second category, iterative mathematical search techniques, such as linear programming, non-linear programming and dynamic programming algorithms are included. Non-conventional metaheuristic search-based techniques, which are used by researchers in recent times are based on genetic algorithm (GA), Tabu search (TS), simulated annealing (SA).

The approach adopted by Taguchi is very popular for solving optimization problems in the field of manufacturing engineering [5, 7, 8, 9]. The method utilizes experimental design called orthogonal array design, and S/N ratio which serve the objective function to be optimized within experimental domain. Traditional Taguchi method solve only single response optimization problem. But in real time most of the engineering application problems are multi-response in nature. In multiple response optimum setting of control factors, it can be observed that an increase/improvement of one response may cause change in another response, beyond the acceptable limit. To solve multi-response optimization problems, it is convenient to convert all the objectives into an equivalent single objective function. This equivalent objective function, which is the representative of all the quality characteristics of the product, is to be optimized. The more frequently used approach is to assign a weighting for each responses. The weighted S/N ratio of each quality characteristics is used to compute the performance measures [10]. In practice it is not competent because it uses engineering judgment and past experiences to optimize multiple responses. To overcome the limitation the combined approaches are proposed by researchers [11, 12, 13, 14, 15].

The grey relational analysis theory, initialized by Deng [16], makes use of this to handle uncertain systematic problem with only partial known information. This theory is adopted for solving the complicated interrelationships among the multiple responses. The grey relational coefficient can express the relationship between the desired and actual experimental results. A grey relational grade is obtained to evaluate the multi-response. Optimization of the complicated multi-response can be converted into optimization of a single grey relational grade. The integrated grey based Taguchi method combines advantages of both grey relational analysis and Taguchi method. This method was successfully applied to optimize the multi-response of complicated problems in manufacturing processes [14, 17]. Furthermore, ANOVA is performed to see which process parameters are statistically significant [18]. In this study, the effect of CNC turning parameters on power consumption and surface roughness are reported using grey based Taguchi method.

2. GREY BASED TAGUCHI METHOD

The integrated Grey based Taguchi method combines the algorithm of Taguchi method and grey relational analysis to determine the optimum process parameters for multiple responses.

2.1 Taguchi Method

The concept of the Taguchi method is that the parameter design is performed to reduce the sources of variation on the quality characteristics of product, and reach a target of process robustness [19]. It utilizes the orthogonal arrays from experimental design theory to study a large number of variables with a small number of experiments [3, 20]. Furthermore, the conclusions drawn from small scale experiments are valid over the entire experimental region spanned by the control factors and their level settings. A loss function is defined to calculate the deviation between the experimental value and the desired value. The value of the loss function is further transformed into an S/N ratio. Usually, there are three categories of performance characteristic in the analysis of the S/N ratio, i.e. lower-the-better, higher-the-better, and nominal-the-best. The S/N ratio η_{ij} for the i^{th} performance characteristic in the j^{th} experiment can be expressed as:

$$\eta_{ij} = -10\log(L_{ij}) \qquad (1)$$

The loss function L_{ij} for higher-the-better performance characteristic can be expressed as:

$$L_{ij} = \frac{1}{n}\sum_{k=1}^{n}\frac{1}{y_{ijk}^2} \qquad (2)$$

L_{ij} - loss function of the i^{th} process response in the jth experiment, k- number of tests,
y_{ijk} - experimental value of the i^{th} performance characteristic in the j^{th} experiment at the k^{th} tests

For lower-the-better performance characteristic, the loss function L_{ij} can be expressed as:

$$L_{ij} = \frac{1}{n}\sum_{k=1}^{n} y_{ijk}^2 \qquad (3)$$

For nominal-is-best performance characteristics, the S/N ratio can be expressed as:

$$\eta_{ij} = 10\log\left(\bar{y}^2 / \sigma\right) \qquad (4)$$

The S/N ratio for each level of process parameters is computed based on the S/N analysis. Regardless of the category of the performance characteristic, a larger S/N ratio corresponds to a better performance characteristic. This S/N ratio value can be considered for the optimization of single response problems. However, optimization of multi-response cannot be straightforward as in the optimization of a single response [21]. The higher S/N ratio for one response may correspond to the lower S/N ratio for another response. To overcome the limitation combined approaches are proposed by researchers. In this, grey based Taguchi method is adopted to optimize the multi-response.

2.2 Grey Relational Analysis

The grey relational analysis based on the grey system theory can be used to solve the complicated interrelationships among the multiple responses effectively. In a grey system, some information is known and some information is unknown. It is applied in optimization of WEDM process, EDM process, chemical-mechanical polishing process and drilling operation with multi-responses [12, 13, 14, 22, 23].

Data pre-processing is the first stage in grey analysis since the range and unit in one data sequence may differ from the others. Data pre-processing is a means of transferring the original sequence to a comparable sequence. Depending on the characteristics of a data sequence, there are various methodologies of data pre-processing available for this analysis.

Experimental data y_{ij} is normalized as Z_{ij} ($0 \le Z_{ij} \le 1$) for the i^{th} performance characteristics in the j^{th} experiment can be expressed as:

For S/N ratio with Larger-the-better condition

$$Z_{ij} = \frac{y_{ij} - \min\left(y_{ij}, i = 1,2,.....n\right)}{\max\left(y_{ij}, i = 1,2,.....n\right) - \min\left(y_{ij}, i = 1,2,......n\right)} \qquad (5)$$

For S/N ratio with smaller-the-better

$$Zij = \frac{\max\left(y_{ij}, i = 1,2,.....n\right) - y_{ij}}{\max\left(y_{ij}, i = 1,2,......n\right) - \min\left(y_{ij}, i = 1,2,.....n\right)} \qquad (6)$$

For S/N ratio with nominal-the-best

$$Zij = \frac{(y_{ij} - \text{Target}) - \min(|y_{ij} - \text{Target}|, i = 1, 2, ...n)}{\max(|y_{ij} - \text{Target}|, i = 1, 2, ...n) - \min(|y_{ij} - \text{Target}|, i = 1, 2, ...n)} \quad (7)$$

According to Deng [15], larger normalized results correspond to better performance and the best normalized result should be equal to one. Then, the grey relational coefficients are calculated to express the relationship between the ideal (best) and the actual experimental results.

The Grey relational Co-efficient γ_{ij} can be expressed as:

$$\gamma_{ij} = \frac{\Delta\min + \xi\Delta\max}{\Delta_{oj}(k) + \xi\Delta\max} \quad (8)$$

Where,

a. j=1,2…n; k=1,2…m, n is the number of experimental data items and m is the number of responses.
b. y_o(k) is the reference sequence ($y_o(k)$=1, k=1,2…m); $y_j(k)$ is the specific comparison sequence.
c. $\Delta_{oj} = \|y_o(k) - y_j(k)\|$ = The absolute value of the difference between $y_o(k)$ and $y_j(k)$
d. $\Delta_{\min} = \min_{\forall j \in i} \min_{\forall k} \|y_o(k) - y_j(k)\|$ is the smallest value of $y_j(k)$
e. $\Delta_{\max} = \max_{\forall j \in i} \max_{\forall k} \|y_o(k) - y_j(k)\|$ is the largest value of $y_j(k)$
f. ξ is the distinguishing coefficient which is defined in the range $0 \le \xi \le 1$ (the value may adjusted based on the practical needs of the system)

The Grey relational grade $\overline{\gamma_j}$ is expressed as:

$$\overline{\gamma_j} = \frac{1}{k}\sum_{i=1}^{m}\gamma_{ij} \quad (9)$$

Where $\overline{\gamma}_j$ is the grey relational grade for the j^{th} experiment and k is the number of performance characteristics. The grey relational grade shows the correlation between the reference sequence and the comparability sequence. The evaluated grey relational grade varies from 0 to 1 and equals 1 if these two sequences are identically coincident. The higher grey relational grade implies the better product quality; on the basis of grey relational grade, the factor effect can be estimated and the optimal level for each controllable factor can also be determined. The structure of the integrated grey based Taguchi algorithm is illustrated in Figure 1.

3. DETERMINATION OF OPTIMAL MACHINING PARAMETERS

3.1 Experimental details

A CNC lathe (FANUC control) with 7.5KW spindle power and maximum spindle speed of 4500 rpm is used to perform the machining operation. A schematic diagram of the experimental set-up used in this study is shown in Figure 2. FLUKE 43B Power Quality Analyzer is connected to the power supply of CNC turning center for measuring the power consumption (Watts) of cutting process. Power consumption is measured for each setting of machining operation and idle running operation. The surface roughness (Ra in μm) is measured using Taylor-Hobson Talysurf which is a stylus and skid type instrument is working on carrier modulating principle. The work material is AISI304 Stainless Steel in the form of round bars with 50mm diameter and 200 mm cutting length. Carbide tool inserts of standards CNMG1200404, CNMG1200408 and CNMG1200412 are used for machining.

To perform the experimental design, three levels of machining parameters cutting speed, feed rate, depth of cut and nose radius are selected and are shown in Table I. To select an appropriate orthogonal array for the experiments, the total degrees of freedom need to be computed. The degrees of freedom for the orthogonal array should be greater than or equal to those for the process parameters. In this study, an L_{27} orthogonal array is used because it has 26 degrees of freedom more than the 8 degrees of freedom in the machining parameters. The experimental combinations of the machining parameters using the L_{27} orthogonal array are presented in Table II. Based on the designed orthogonal array combination turning operations are performed in CNC lathe. The experimental results are summarized in Table II.

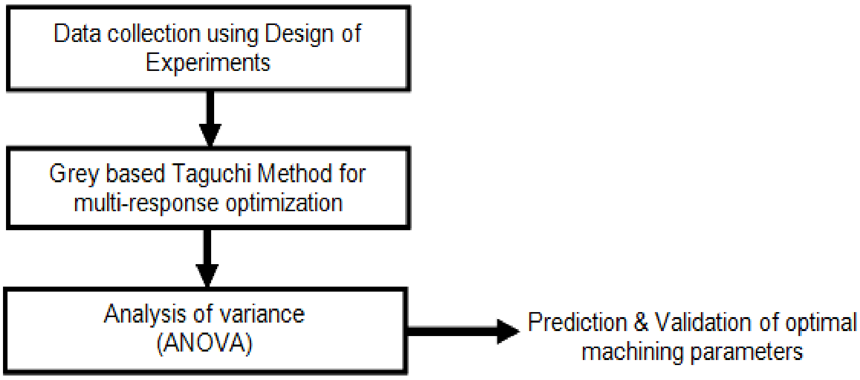

Figure 1: Structure of Grey based Taguchi method.

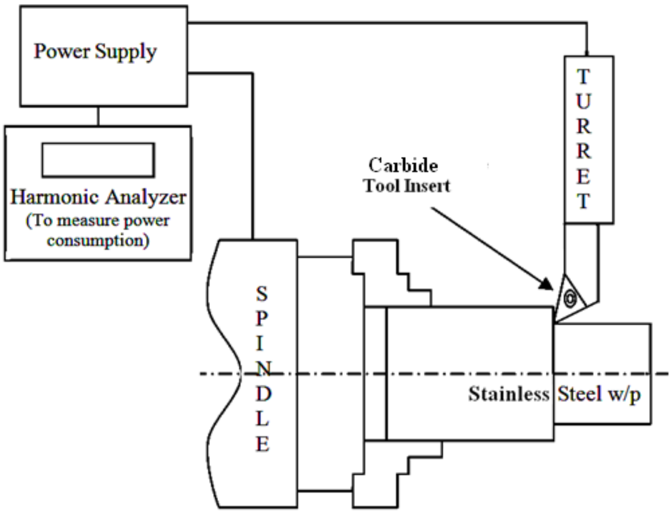

Figure 2: Schematic diagram of experimental set-up.

Table I: Cutting parameters and their levels.

Factor	Cutting Parameter	Unit	Level 1	Level 2	Level 3
A	Cutting speed ‘V’	m/min	100	125	150
B	Feed rate ‘f’	mm/rev	0.05	0.1	0.15
C	Depth of cut ‘d’	mm	0.20	0.35	0.50
D	Nose radius ‘NR’	mm	0.4	0.8	1.2

3.2 Optimization of machining parameters

Initially, the S/N ratios for a given responses are computed using one of the (1), (2), (3) and (4) depending upon the type of quality characteristics. Power consumption and surface roughness have lower-the-better criterion.

The normalized values for each response S/N ratios are estimated using (5), (6) and (7). The computed S/N ratios for each quality characteristic and the normalized values of S/N ratios are shown in Table III.

Table II: Experimental design using L_{27} orthogonal array and their responses.

Exp. No.	A	B	C	D	Power consumption (Watts)	Surface roughness (Ra in µm)
1	1	1	1	1	213	2.04
2	1	1	2	2	320	1.74
3	1	1	3	3	332	2.02
4	1	2	1	2	283	1.25
5	1	2	2	3	340	1.1
6	1	2	3	1	393	1.02
7	1	3	1	3	275	1.5
8	1	3	2	1	350	1.12
9	1	3	3	2	620	1.35
10	2	1	1	2	392	1.82
11	2	1	2	3	438	1.52
12	2	1	3	1	441	1.78
13	2	2	1	3	391	1.04
14	2	2	2	1	570	0.84
15	2	2	3	2	668	1.02
16	2	3	1	1	394	1.16
17	2	3	2	2	617	1.26
18	2	3	3	3	760	1.48
19	3	1	1	3	448	2.02
20	3	1	2	1	516	1.54
21	3	1	3	2	585	1.94
22	3	2	1	1	476	1.08
23	3	2	2	2	625	1.16
24	3	2	3	3	765	1.42
25	3	3	1	2	528	1.46
26	3	3	2	3	706	1.38
27	3	3	3	1	873	1.64

Grey relational coefficient for each response has been calculated using (8). The value for ξ is taken as 0.5 since both the process parameters are of equal weight. The results are shown in Table III. The grey relational grade can be calculated by using (9), which is the overall representative of both the responses shown in Table III. Now, the multi-response optimization problem has been transformed into a single equivalent objective function optimization problem using this approach. The higher grey relational grade is said to be close to the optimal. The mean response table for overall grey relational grade is shown in Table IV and is represented graphically in Figure 3. The mean grey relational grade for the cutting speed at levels 1, 2 and 3 can be calculated by averaging the grey relational grades for the experiments 1-9, 10-18 and 19-27 respectively. The mean grey relational grade for each level of the other parameters can be computed in the similar way. With the help of the Table

IV and Fig 3, the optimal parameter combination has been determined. The optimal factor setting condition is $A_1B_2C_1D_1$.

Using the grey relational grade value, ANOVA is formulated for identifying the significant factors. The results of ANOVA are presented in Table V. From ANOVA, it is clear that cutting speed (35.47%) influences more on turning of Stainless steel AISI 304 followed by feed rate (26.12%), depth of cut (18.16%) and nose radius (10.63%).

Table III: S/N ratios and Grey relational coefficients of responses and Grey relational grade.

Exp. No.	S/N ratios		Normalized values of S/N ratios		Grey Relational Coefficient of		Grey relational grade
	Power Consumption	Surface Roughness	Power Consumption	Surface Roughness	Power Consumption	Surface Roughness	
1	-46.5676	-6.1926	1.0000	0.0000	1.0000	0.3333	0.6667
2	-50.1030	-4.8110	0.7115	0.1793	0.6341	0.3786	0.5063
3	-50.4228	-6.1070	0.6854	0.0111	0.6138	0.3358	0.4748
4	-49.0357	-1.9382	0.7986	0.5520	0.7128	0.5274	0.6201
5	-50.6296	-0.8279	0.6685	0.6961	0.6013	0.6220	0.6116
6	-51.8879	-0.1720	0.5658	0.7812	0.5352	0.6956	0.6154
7	-48.7867	-3.5218	0.8189	0.3465	0.7341	0.4335	0.5838
8	-50.8814	-0.9844	0.6479	0.6758	0.5868	0.6066	0.5967
9	-55.8478	-2.6067	0.2426	0.4653	0.3976	0.4832	0.4404
10	-51.8657	-5.2014	0.5676	0.1286	0.5362	0.3646	0.4504
11	-52.8295	-3.6369	0.4889	0.3316	0.4945	0.4279	0.4612
12	-52.8888	-5.0084	0.4841	0.1537	0.4922	0.3714	0.4318
13	-51.8435	-0.3407	0.5694	0.7593	0.5373	0.6750	0.6062
14	-55.1175	1.5144	0.3022	1.0000	0.4174	1.0000	0.7087
15	-56.4955	-0.1720	0.1897	0.7812	0.3816	0.6956	0.5386
16	-51.9099	-1.2892	0.5640	0.6362	0.5342	0.5789	0.5565
17	-55.8057	-2.0074	0.2460	0.5430	0.3987	0.5225	0.4606
18	-57.6163	-3.4052	0.0983	0.3617	0.3567	0.4392	0.3980
19	-53.0256	-6.1070	0.4729	0.0111	0.4868	0.3358	0.4113
20	-54.2530	-3.7504	0.3728	0.3169	0.4436	0.4226	0.4331
21	-55.3431	-5.7560	0.2838	0.0566	0.4111	0.3464	0.3788
22	-53.5521	-0.6685	0.4300	0.7168	0.4673	0.6384	0.5528
23	-55.9176	-1.2892	0.2369	0.6362	0.3959	0.5789	0.4874
24	-57.6732	-3.0458	0.0936	0.4083	0.3555	0.4580	0.4068
25	-54.4527	-3.2871	0.3565	0.3770	0.4372	0.4452	0.4412
26	-56.9761	-2.7976	0.1505	0.4405	0.3705	0.4719	0.4212
27	-58.8203	-4.2969	0.0000	0.2460	0.3333	0.3987	0.3660

Table IV Response table (mean) for overall grey relational grade.

Factors	Level-1	Level-2	Level-3
A	0.5684	0.5124	0.4332
B	0.4683	0.5720	0.4738
C	0.5432	0.5208	0.4501
D	0.5475	0.4804	0.4861

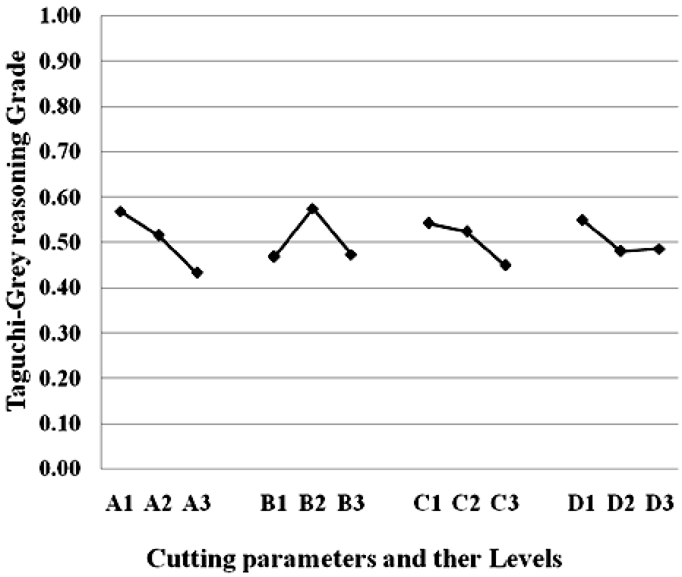

Figure 3: The response graph for each level of machining parameters.

Table V: Results of the ANOVA.

Factor	DOF	SS	MS	F value	% Contribution
A	2	0.0831	0.0416	33.20	35.47
B	2	0.0612	0.0306	24.45	26.12
C	2	0.0426	0.0213	16.99	18.16
D	2	0.0249	0.0125	9.95	10.63
Error	18	0.0225	0.0013	-	9.62
Total	26	0.2344	-	-	100.00

3.3 Predicted optimum condition

In order to predict the optimum condition, the expected mean at the optimal settings (μ) is calculated by using the following model.

$$\mu = \bar{A}_1 + \bar{B}_2 + \bar{C}_1 + \bar{D}_1 - 3\times\bar{T}_{gg} \tag{10}$$

Where, $\bar{A}_1$, $\bar{B}_2$, $\bar{C}_1$ and $\bar{D}_1$ are the mean values of the grey relational grade with the parameters at optimum levels and $\bar{T}_{gg}$ is the overall mean of average grey grade. The expected mean (μ) at optimal setting is found to be 0.7171.

Confidence interval (CI) is calculated as

$$CI = \sqrt{F_\alpha(1, f_e)V_e\left[\frac{1}{n_{eff}} + \frac{1}{R}\right]} \tag{11}$$

= $\pm$ 0.0857

Where, $F_\alpha(1, f_e)$ is the F ratio at a significance level of α %, α is the risk, f_e is the error degrees of freedom, V_e is the error mean square, n_{eff} is the effective total number of tests and R is the number of confirmation tests

$$n_{eff} = \frac{\text{Total number of observations}}{1+\text{Total degrees of freedom associated with items used in estimating } \mu} \quad (12)$$

Therefore 95% confidence interval of the predicted optimum condition is given by following model, where μ = the Grey relational grade value after conducting the confirmation experiments with optimal setting point, i.e., $A_1B_2C_1D_1$

(0.7171-0.0857) < μ < (0.7171+0.0857)

(0.6314)< μ < (0.8028)

4. CONFIRMATION TEST

Once the optimal level of the process parameters has been determined, the final step is to predict and verify the improvement of the responses using the optimal level of process parameters. Table VI shows the comparison of the multi-response for initial and optimal machining parameters. The initial designated levels of machining parameters are A_1, B_1, C_2 and D_2 which is the second experiment shown in the Table II. As noted from Table VI, the surface roughness Ra is decreased from 1.74 µm to 1.14 µm and the power consumption is decreased from 320 watts to 245 watts respectively. The estimated grey relational grade is increased from 0.5063 to 0.7134, which is the largest value obtained in all the experimental results in Table III. It is clearly shown that the multi-responses in the turning process are together improved by using this method.

Table VI: The comparison results of initial and optimal turning responses.

Initial turning parameters		Optimal turning parameters	
		Prediction	Experiment
Levels	$A_1B_1C_2D_2$	$A_1B_2C_1D_1$	$A_1B_2C_1D_1$
Power consumption (Watts),	320	-	245
Surface roughness (Ra)	1.74	-	1.14
Taguchi based grey relational grade	0.5063	0.7171	0.7134
Improvement of Taguchi based grey relational grade		0.2108	0.2071

5. CONCLUSION

Experiments are designed and conducted on CNC machine with carbide tool inserts and Stainless Steel AISI304 as work material to optimize the turning parameters. The power consumption and surface roughness are the responses. The proposed Grey based Taguchi method is constructive in optimizing the multi-responses. It is identified that cutting speed influences (35.47%) more, followed by feed rate (26.12%), depth of cut (18.16%) and nose radius (10.63%). Confirmation test results proved that the determined optimum condition of turning parameters satisfy the real requirements.

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THE INTEGRATION OF THE STANDARDIZED SPECIFICATIONS (ISO–GPS) IN MANUFACTURING DIMENSIONS

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Abstract:
The transfer of the definite functional geometrical model following the formalism GPS (Geometrical Product Specification) to the equivalent model of the unidirectional (1D) simulation of manufacture should be carried out following an interface. In addition, the simulated intermediate geometries of the part providing from various phases of the manufacturing process should also be transformed in their turn, in standardized specifications. In this context, an interfacing was developed in order to use the results of simulation in the industrial field. This interface which was conditioned by certain assumptions and the apparition of certain constraints is the result of a logical reasoning of setting in position of reference surfaces compared to those which are useful in the isostatism. In this paper, we will develop the interface of transformation of the results of the dimensions manufacturing (1D) in ISO system (GPS). GPS language allows management of communication with distant partners (Globalization). Dimensions chains (1D) make the problem following one direction. In this sense, this type of model is not able to transform the introduced nuances by all geometric specifications, or reference systems. Their applications are restricted to the analysis and synthesis of tolerances for dimensional specifications or localization. We will also present the developed software and an example of treatment.

Key Words: Interfacing, Standardized specifications, Dispersions, GPS, CAM.

1. INTRODUCTION

The appearance of ISO-GPS norms was on December 1996. They serve to compensate the problem of ignorance of geometrical specifications norms which entailed dysfunctions in the states of design, manufacturing and metrology of a mechanical system.

The engineering and design department carries out the design drawing, which is expressed by standardized specifications. In addition the process of cutting simulation requires the installation of an equivalent model [1], [2]. This last once simulated, gives the manufacturing dimension which is not defined according to GPS formalism (Geometrical Product Specification). It will be necessary, once again to translate these manufactured dimensions of the production drawing into standardized specifications. It requires a development of an interface of passage of a model to another as shown in Figure 1.

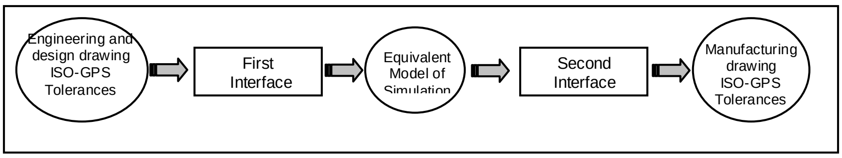


Figure 1: Problems of passage of the ISO model to equivalent model.

This problematic may be expressed more precisely by the process of simulation illustrated by Figure 2. Under the assumptions of the negligence of orientation defects between surfaces of references and of the form defects of these surfaces, it is possible to approach the unidirectional conditions. In the same way, additional constraints must be imposed for the passage of the intermediate geometries to the manufacturing drawing specified in ISO (GPS).

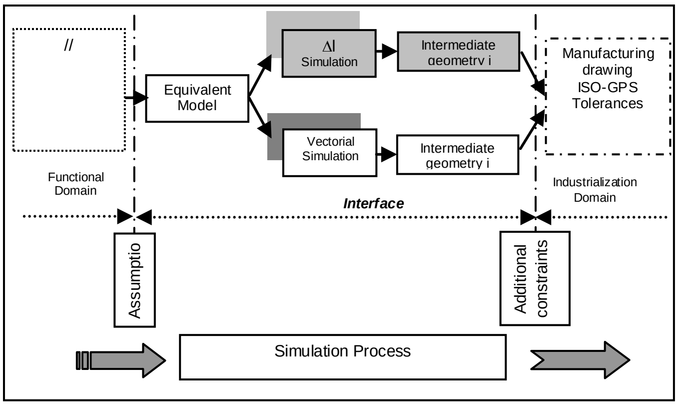


Figure 2: Simulation process.

2. ASSUMPTIONS

The design drawing of the application example of the part of turning process (Figure 3), can be schematized without taking into account the assumptions of negligence of orientation defects between surfaces and form defects of these surfaces.

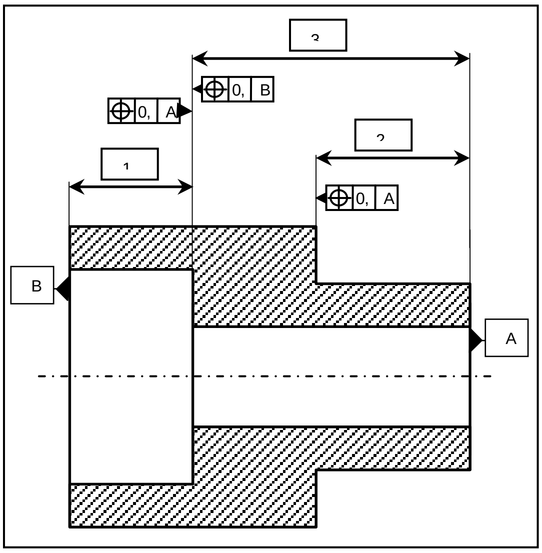


Figure 3: Definition drawing of the workpiece.

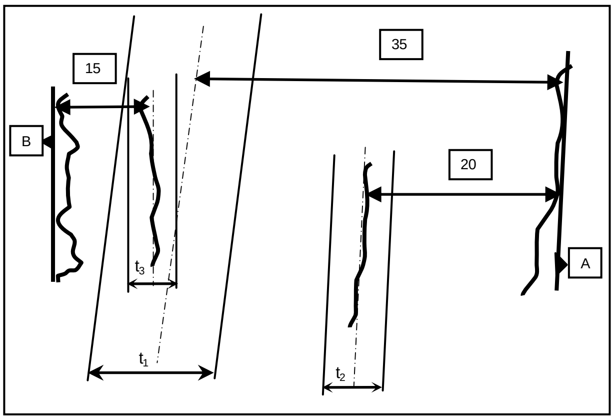


Figure 4: Drawing with orientation and form defects.

The specification of the localization is not enough to dimension a drawing. Since there is no orientation specification which connects surfaces of references between them, we obtain drawings similar to the drawings of the real models shown in Figure 4.

The unidirectional model supposes that each surface, line or projected point orthogonally on the direction of simulation, is represented by a point of substitution located outside the workpiece [3], [4]. This supposed to represent the real geometry of the workpieces. Consequently, if the orientation and form defects are significant, we observe the situations illustrated by left parts of figures 5 and 6. In order to obtain projections of surfaces on the direction of the simulation points (points of substitution), it will be necessary to consider the orientation defects as shown in Figure 5.

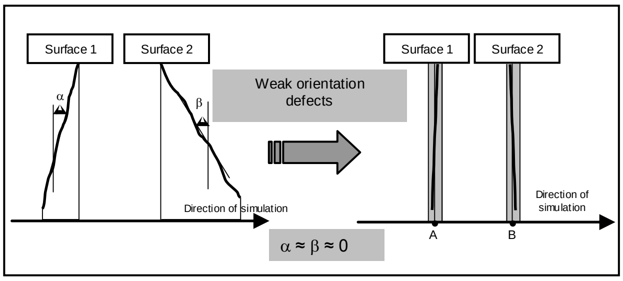


Figure 5: Assumptions of weak orientation defects.

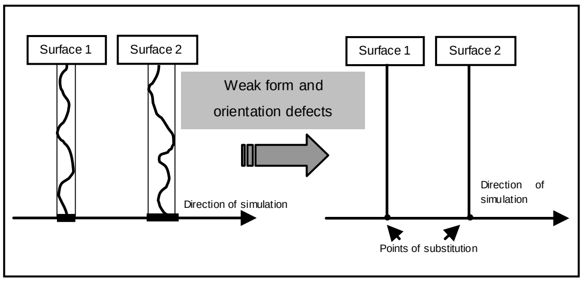


Figure 6: Assumptions of weak form and orientation defects.

In addition, if the case where form defects are not significant, the projection of surfaces 1 and 2 on the direction of simulation gives segments which tend towards the points of substitution (Figure 6).

Under the assumptions of weak form and orientation defects, the interpretation of Figure 4 becomes Figure 7.

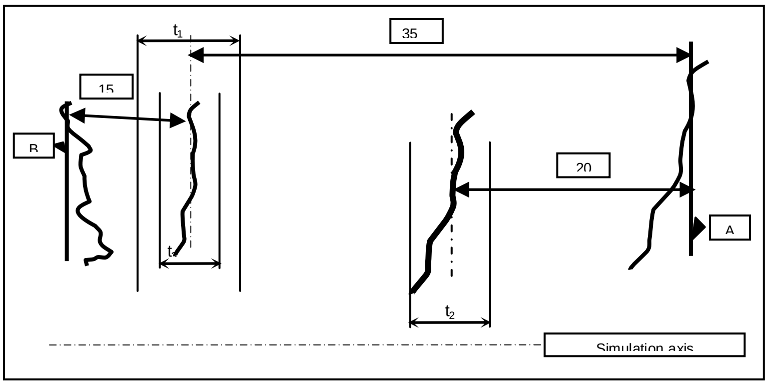


Figure 7: Drawing without orientation and form defects.

Under the assumption of the ignorance of orientation and form defects between surfaces of references, the passage of the functional model to the equivalent model of simulation is possible.

3. PASSAGE OF THE SIMULATION TO THE ISO MODEL

From the equivalent model of simulation, we can specify the intermediate geometries of manufacturing in specifications of localization and in orientation and form specifications [5].

3.1 Specifications of localization

The manufacturing dimensions resulting from simulation are dependent on the previously assumed assumptions. From manufacturing process, we have surfaces of reference (recovery) which represent surfaces of references to the isostatism for the intermediate geometries. From these surfaces, the manufacturing dimensions into specifications of localization can be converted [6], [7] as shown in Figure 8.

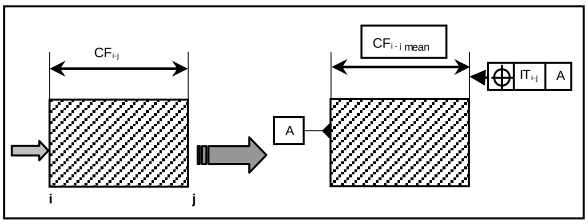


Figure 8: Conversion of manufacturing dimension to normalised specification.

3.2 Orientation and form specifications

According to the manufacturing process, additional constraints on surfaces of references must be added in order to respect the previous assumptions. The technology of the isostatism (integral or punctual) can involve the addition of a form constraint.

While the defect of orientation appear mainly between the group of surfaces being used for the isostatism and the group of machined surfaces when they are considered to be surface references.

The considerations of these additional geometrical specifications are defined in first approach by the following rules of decision:

- **If** all surfaces of reference EDD (Engineering and Design Department) serves as surfaces of isostatism **then:**

  If surfaces of references SRi are machined in the same phase, **then** there is no additional geometrical constraint. They are obtained in "geometry of machine" (Figure 9).

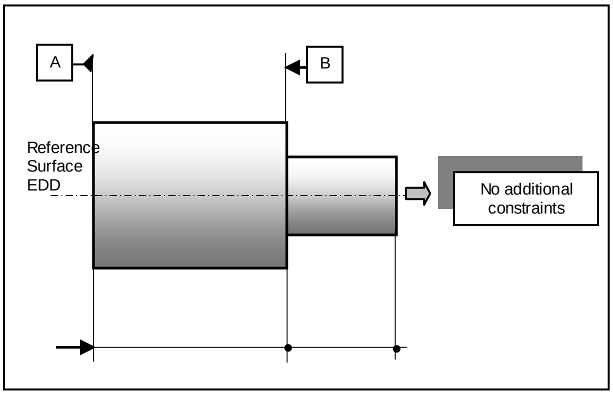


Figure 9: Geometry of machine.

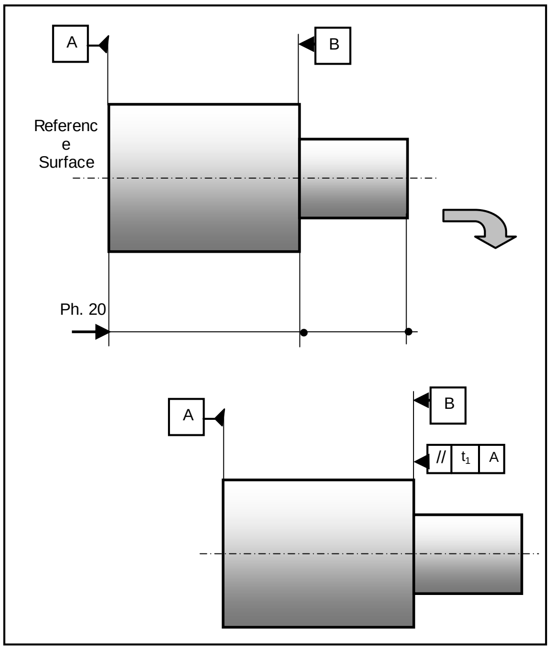


Figure 10: Integral isostatism.

- **If not** SRi surfaces are realised in several phases **then**
  - **If** the isostatism is integral, **then** there is addition of a constraint of orientation between the surfaces of reference SRi (Figure 10).
  - **If** the isostatism is punctual, then there is addition of an orientation constraint between surfaces of reference and a constraint of form on the surface of reference EDD being useful like reference to the isostatism in the considered phase.
  - **If not,** there are surfaces of reference EDD which were not useful as surfaces of reference to the isostatism, **then** in this case, we impose constraints of orientation between these surfaces and surfaces of reference to the isostatism in the phase where they are machined, in order to respect the assumptions described previously.

These rules are founded on a logical reasoning of the setting in position of surfaces of references to the isostatism. They are regrouped and ordered in a flowchart of addition of the specifications of orientation and form of Figure 11 [8]. This chart is based on algorithms related to the concept of expert systems " *If* condition *Then* action ".

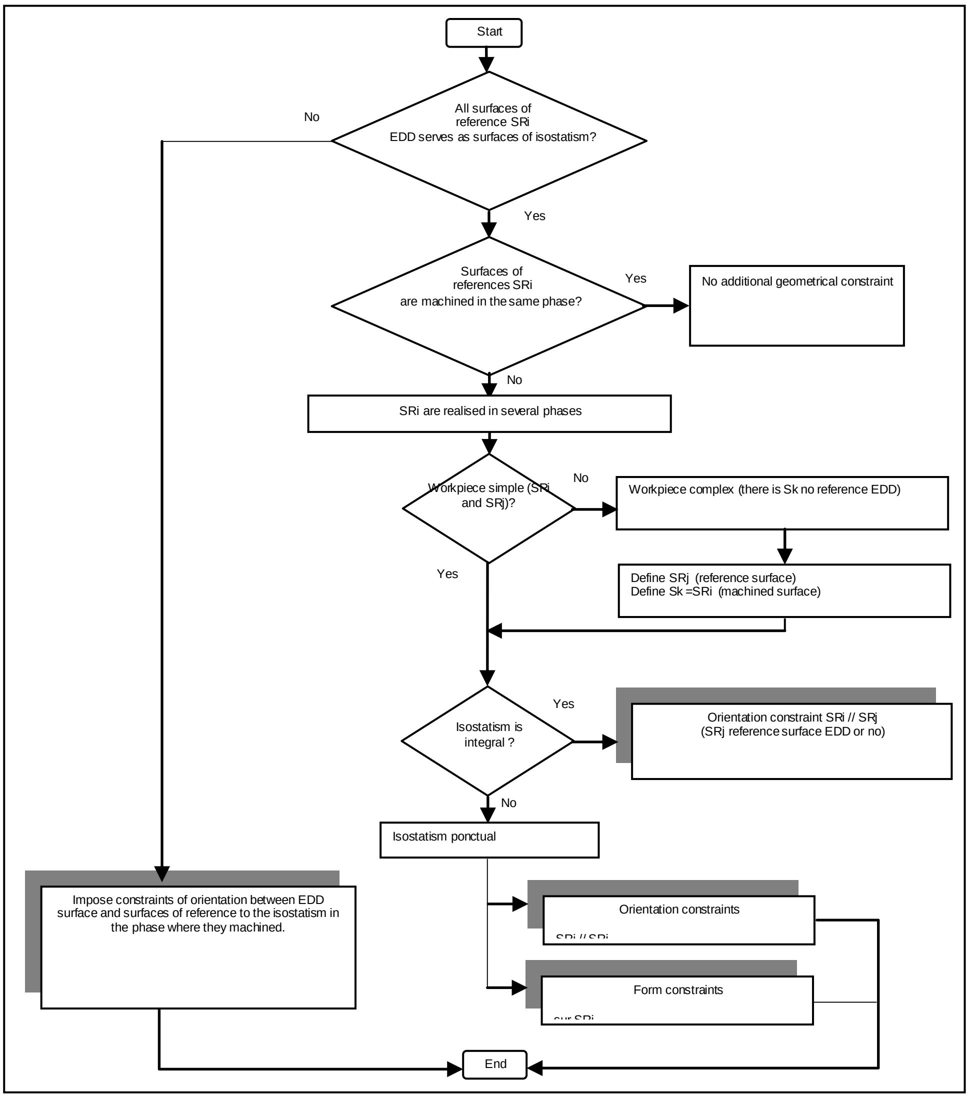
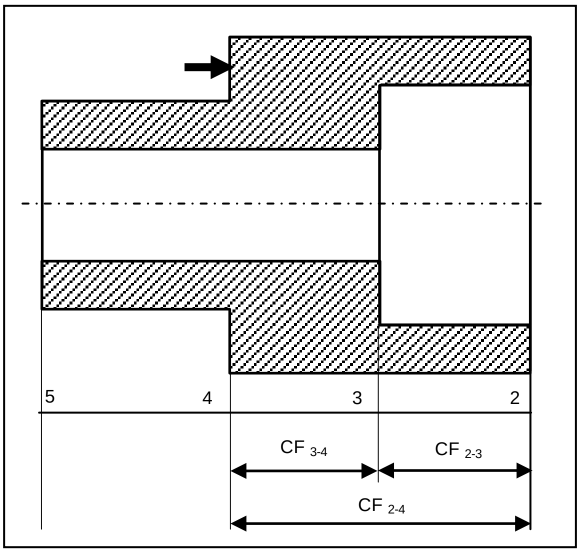


Figure 11: Flowchart of additional orientation and form specifications.

In order to illustrate these remarks, we apply these rules to the final geometry of phase 20 of the defined manufacturing process of the part in turning (Figure 3). We obtain the following results:



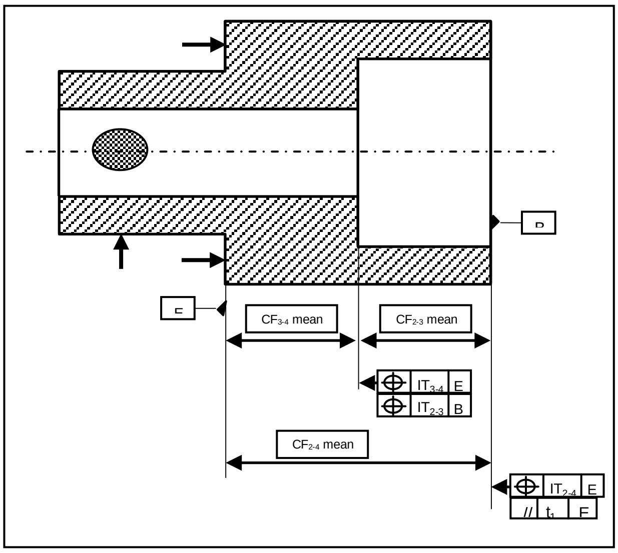


Figure 12: Final Geometry of phase 20. Figure 13: Manufacturing drawing of phase 20.

4. AUTOMATION OF THE INTERFACING

Automation was made on the basis of geometrical relations between, both localization and parallelism constraints, and parallelism and form constraints (flatness). This is done by respecting the descending order of the tolerances [9], as illustrated in Figure 14.

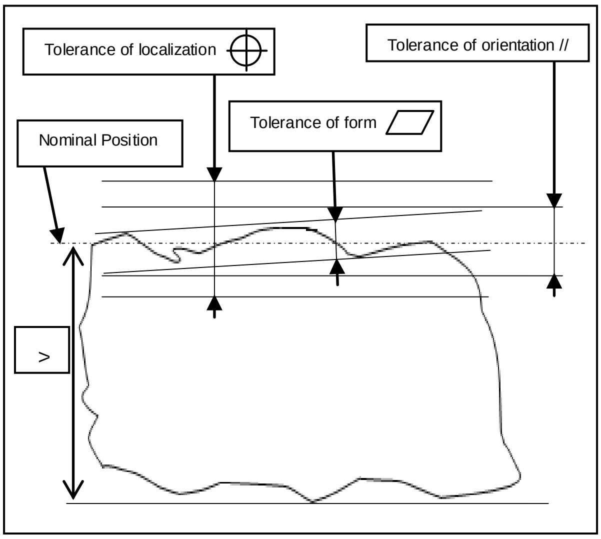


Figure 14: Order of the tolerances.

4.1 Mathematical modeling of the addition of the specifications

4.1.1 Specification of orientation

With an aim of making an approach between the parallelism and localization tolerances and by supposing the beginning of production (the defects due to the machining of the first parts are rather weak), we can then consider that the defect of parallelism (Dp) is sufficiently small so that it is contained in a centered zone compared to the median plane of localization. The localization defect (Dl) is supposed to be very weak, and centered compared to this same median plane, these assumptions are illustrated by Figure 15.

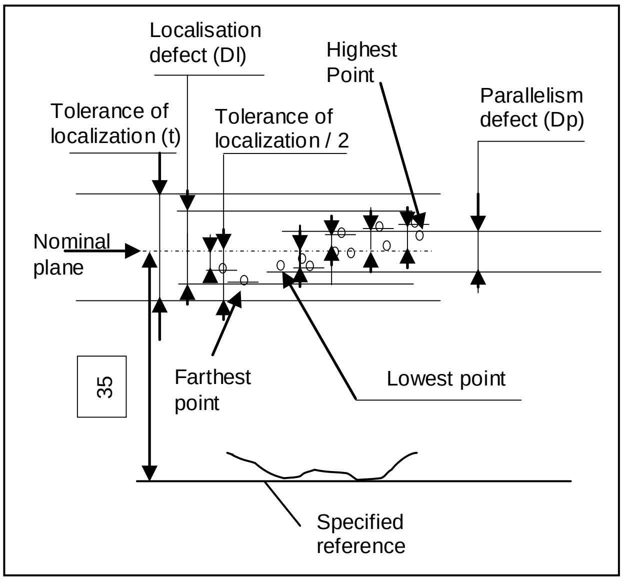


Figure 15: Relation between parallelism and localization in the beginning of production.

Knowing that the specification of localization is satisfied if [8]:

Variation of localization $\leq$ *tolerance of localization/2* (1)

With, Variation of localization = Defect of localization (Dl)/2

Under the assumption of centered production, the median plane is centered. In order to have the tolerance of parallelism is included by the tolerance of localization, as required by the ISO standard [1101] and as shown in Figure 14 (order of the tolerances) [8], it must be less or in the limit case equal to this one:

Tolerance of parallelism (t_1) $\leq$ *tolerance of localization (t)* (2)

Taking the limit case, we obtain:

Tolerance of parallelism (*t1*) *= tolerance of localization* (*t*)

By analogy with the tolerances of the relation (2), if the defects are considered, we can write:

Defect of parallelism (Dp) $\leq$ *Defect of localization (Dl)* (3)

Since we are at the beginning of production, then we can consider that:

Defect of localization (Dl) $\leq$ *tolerance of localization (t)* (4)

It can be interpreted by the following relation:

Defect of localization (Dl) = α ** tolerance of localization (t), with* $\alpha \leq 1$ (5)

According to (3) and taking the limit case, we obtain:

Defect of parallelism (Dp) = Defect of localization (Dl) = α ** tolerance of localization (t), with* $\alpha \leq 1$ (6)

Moreover, in the limit case the defect of parallelism (Dp) is equal to the tolerance of parallelism (t1), therefore we can write the following relation:

t_1 *(//)=*α ** t (⌖) , with* $\alpha \leq 1$ (5-3) (7)

At the end of the production the opposite case is considered, dispersions are very significant, then we can consider that the defect of parallelism is rather large approximately equal to the tolerance of localization. We then consider this defect centered compared to the median plane of localization. As for the defect of localization, it also increased and consequently, we consider it equal to the tolerance of localization. Figure 16 highlights these remarks.

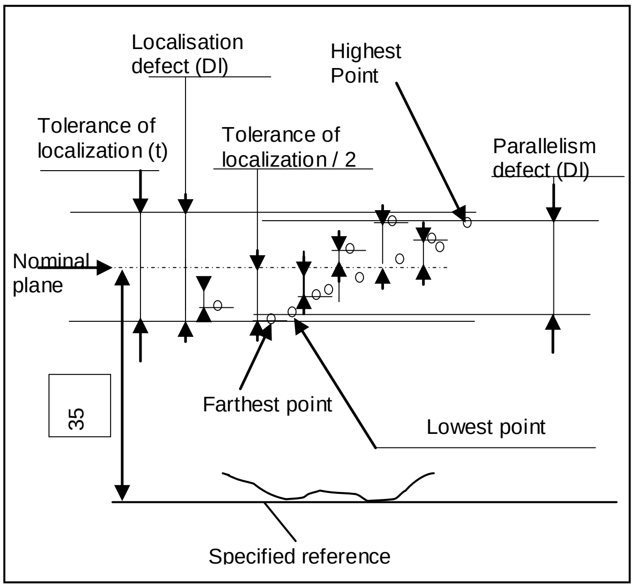


Figure 16: Relation between parallelism and localization in the end of production.

We notice that we can be in different cases, according to values of α (with α strictly between 0 and 1), the application of one of the cases, leads us to a study of reliability / productivity, as illustrated in Figure 17 [9].

To simplify the problem, α is limited to four values (0,25 ; 0,5 ; 0,75 and 1).

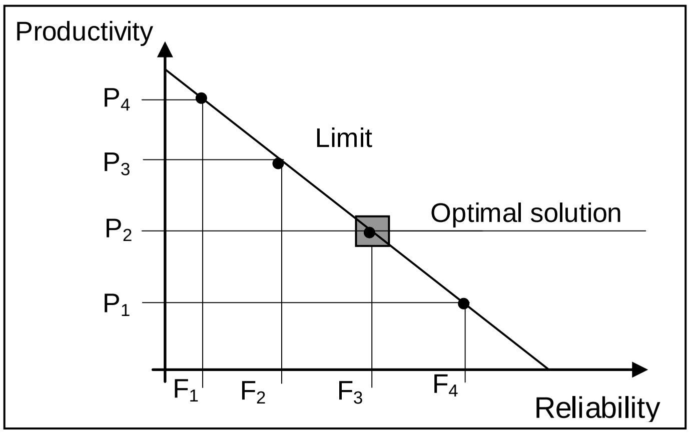


Figure 17: Flowchart of the Reliability / Productivity.

The analysis of the diagram (Figure 17), shows that if we take:

- α = 0,25; so we have t_1(parallelism) = 0,25 * t(localization), therefore we have a very great reliability (F_4) and a very low productivity (P_1).
- α = 0,5; then there are t_1(parallelism) = 0,5 * t(localization), therefore we have a good reliability (F_3) and a good productivity (P_2).
- α = 0,75; we have then t_1(parallelism) = 0,75 * t(localization), therefore we get a medium reliability (F_2) and a great productivity (P_3) .
- On the oder hand, if we take α = 1 ; then t_1(parallelism) = 0,5 * t(localization), therefore we have a great productivity (P_4) and a very low reliability (F_1).

We recapitulate all this interpretation in Table I:

Table I: Relation Reliability / Productivity.

α values	Productivity	Reliability
α = 0,25 (P_1, F_4)	very low	very great
α = 0,5 (P_2, F_3)	good	good
α = 0,75 (P_3, F_2)	Large	Average
α = 1 (P_4, F_1)	very great	very low

During the programmation, we use the optimal solution which gives us a good reliability (F_3 and a good productivity (P_2) α = 0,5 (the gray zone) . It can be represented by the following relation :

$$t_1(//) = 0,5 * t(\oplus) \tag{8}$$

4.1.2 Orientation and form specification

In the case of recovery and if the isostatism consists of ponctuals (example stubborn), then we add an orientation specification (parallelism) on the machined surface (SRi), with respect to the reference frame (SRj) and a shape constraint on the reference frame (SRj). This to ensure *the parallelism between the two plans SRi and SRj*. The value of the tolerance of the additional constraint of parallelism was calculated in 4.1.1. The quantification of the additional form constraint (flatness), leads us to took for a relation between parallelism and flatness. The tolerance of parallelism can include the straightness and flatness tolerances [11]. In other hand, the order of magnitude of the specifications (Figure 14) gives us the descending order of the tolerances. According to these two remarks, we have considered the tolerance of flatness equal to the tolerance of localization divided by four, as illustrated by the following relation.

$$t_2(\square)=0{,}25 * t(\oplus) \quad (9)$$

4.2 Conversion of the CF in specifications of localization

Figure 18, illustrates the flow chart of the conversion procedure of the manufacturing dimensions (CF) in specifications of localization.

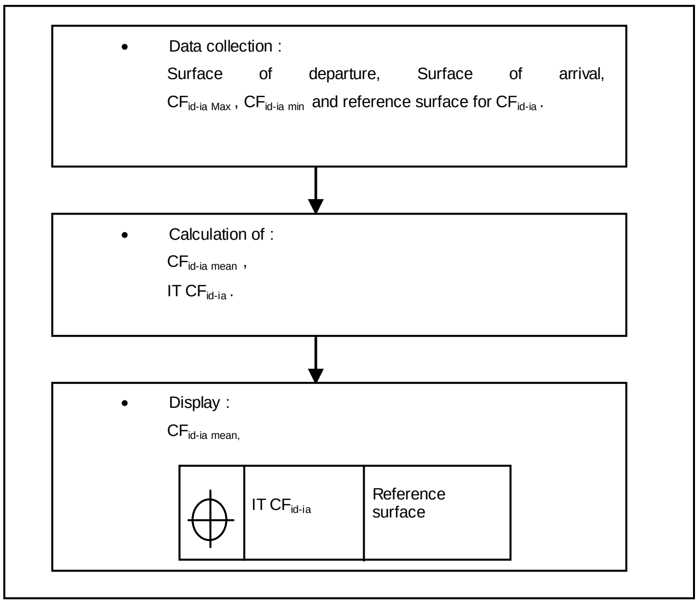


Figure 18: Flowchart of the conversion processor of manufacturing dimensions (CF).

Mathematical calculation is done in two stages:

- *Stage 1: Calculation of CF id-ia mean*

The manufacturing dimension CF id-ia mean represents the arithmetic mean of CF id-ia $_{Max}$ and CF id-ia $_{min}$ as shown in equation 10.

$$CF_{id\text{-}ia\ mean} = \frac{CF_{id-ia\ Max} + CF_{id-ia\ \min}}{2} \quad (10)$$

- *Stage 2: Calculation of IT CF id-ia*

The calculation of the interval of tolerance IT CF id-ia is established on the basis of the difference between CF id-ia $_{Max}$ and CF id-ia $_{min}$ (equation 11).

$$ITCF_{id\text{-}ia} = CF_{id\text{-}ia\ Maxi} - CFid_{\text{-}ia\ mini} \quad (11)$$

4.3 Automation of the addition of the specifications

The addition of form and orientation specifications will be automated according to the case recovery or not of recovery. Figure 19 represents the flowchart of the addition of the specifications.

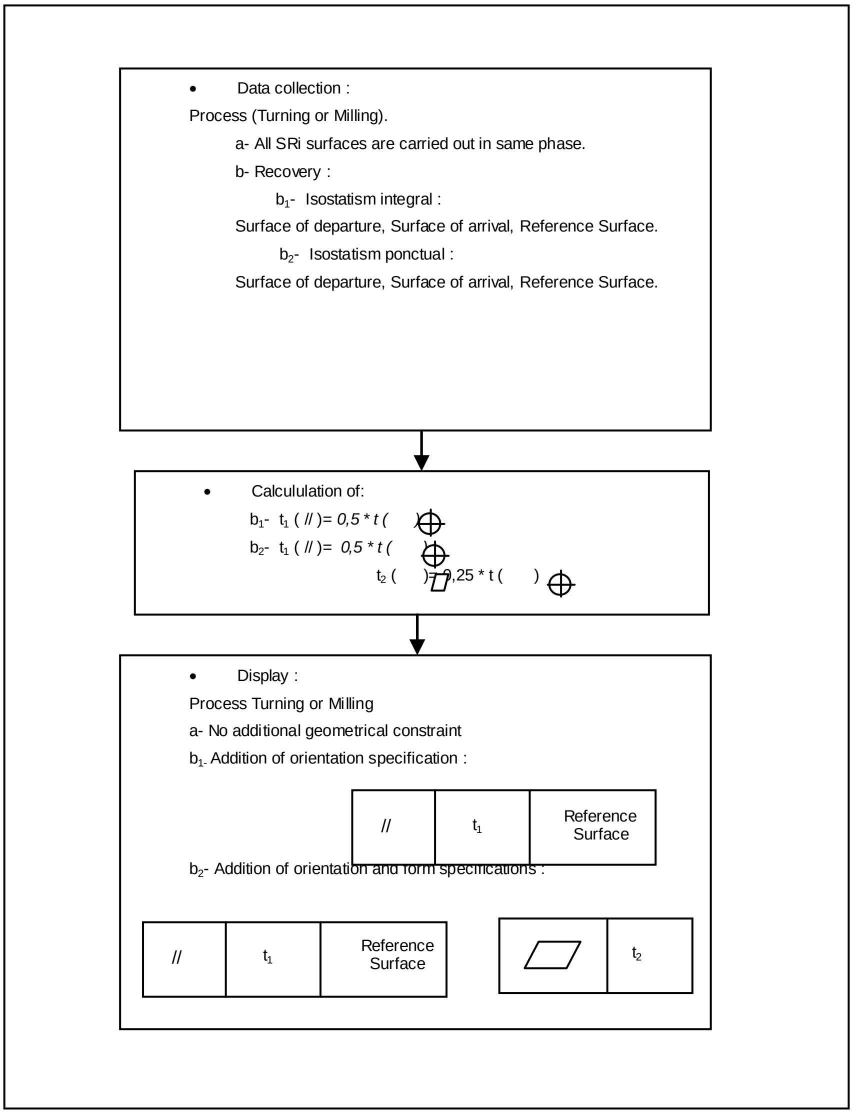
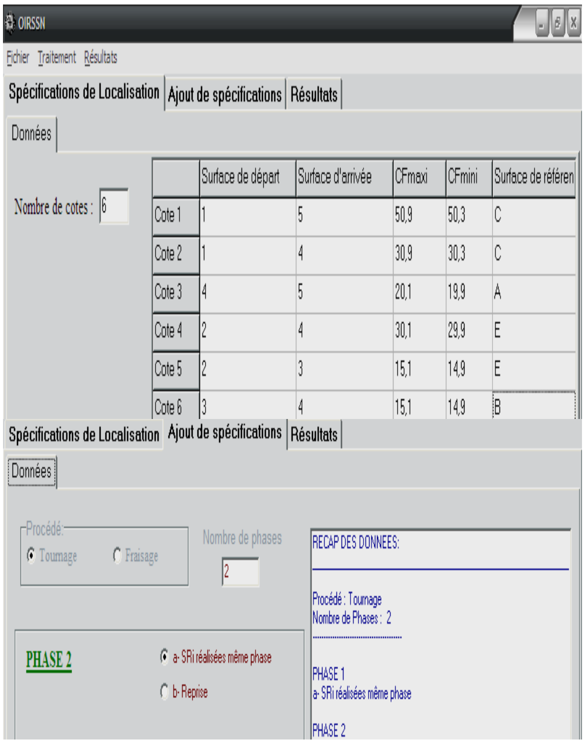


Figure 19: Flowchart of additional form and orientation specifications.

5. PROGRAMMATION AND VALIDATION TESTS

A module was programmed on the basis of the previously given flow chart. This program is named OIRSSN (*Tool of Interfacing of the Results of Simulation in Standardized Specifications)*. It was programmed under Delphi language. The final program was tested on three parts of various morphologies (simple and complex). The results of the automatic treatment agree with those of the manual treatment. We will apply this program "OIRSSN" to <u>the turning workpiece</u> (Figure 3). The screen of Figure 20, represents the data file of the of turning part, and the screen of Figure 21, illustrates the file of the results.



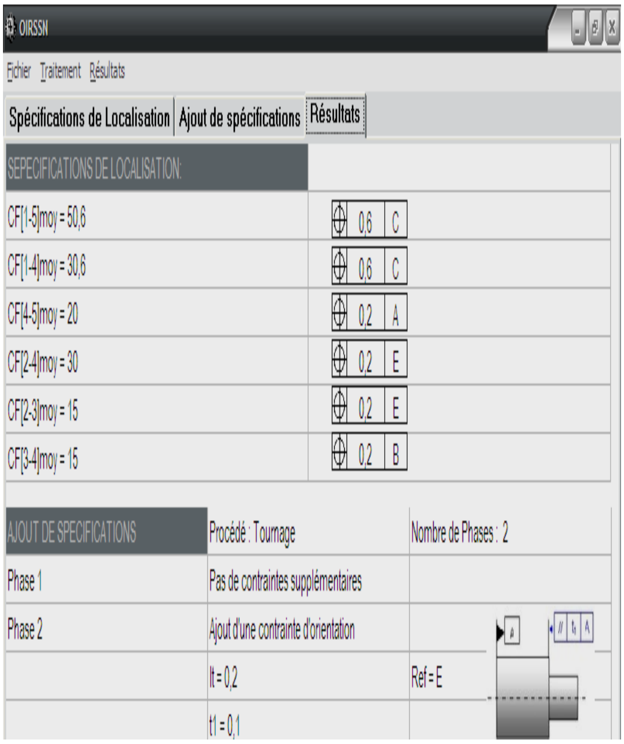


Figure 20: File of data for turning workpiece. Figure 21: File of results for turning workpiece.

Figure 22 represents the manufacturing drawing of phase 20 of the turning part, after automatic treatment.

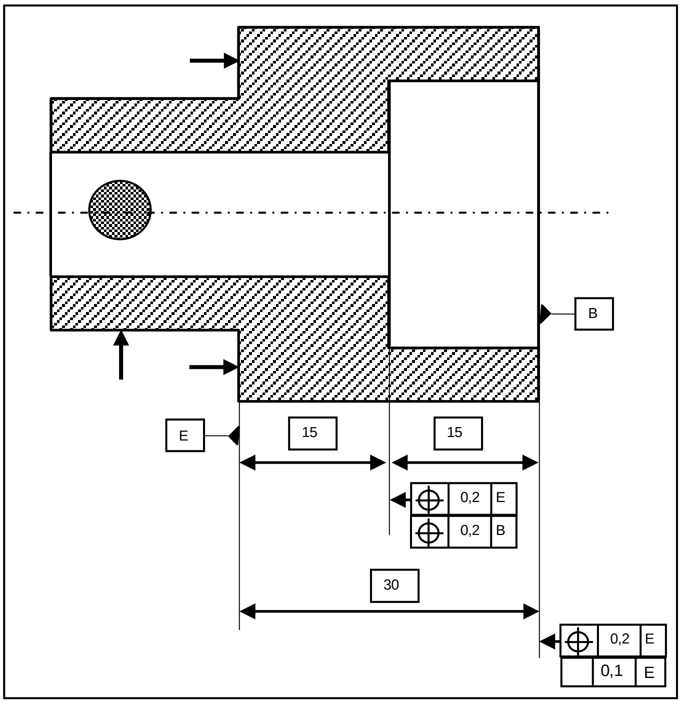


Figure 22: Manufacturing drawing of phase 20 of the turning workpiece after automatic treatement.

Since the isostatism is integral, then we added an orientation constraint (parallelism t_1= 0,1) with respect to this reference plan (surface E) on surface B.

6. CONCLUSION

This paper shows that the passage of the model of unidirectional simulation to a defined model following the GPS formalism is possible. The passage of the functional model specified in ISO system to the model of simulation was conditioned by certain assumptions. The passage of the equivalent model of simulation to the geometrical manufacturing model was balanced by the apparition of certain excess over constraints. These last are the results of a logical reasoning of the setting in position of surfaces of references to the isostatism. The development of this interface leads to convert the results of the manufacturing dimensions into ISO-GPS system. Lastly, the integration of OIRSSN module, as well as the software of the tolerancing manufacturing dimensions the method of dispersions [12] in CAD/CAM system makes it possible to have automatically the manufacturing drawings of the various phases specified in ISO-GPS as final result. In addition their uses as data base for a control while manufacturing (in situ) and the rebuilding in 3D.

NOMENCLATURE

CF manufacturing dimension
i_d surface of departure
i_a surface of arrival
IT interval of tolerance
t_1 parallelism constraint
t_2 flatness constraint
ISO International System Organisation
GPS Geometrical Product Specification

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EXPECTATIONS OF AUTOMATIC PROGRAMMING OF CNC MACHINE TOOLS

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Abstract:
The question arising is how to increase the productivity of creation of CNC programmes and, simultaneously, how to reduce the exactingness of programming. The answer appears in the form of automated programming which is considered to be upgrade and/or a parallel branch of CAM programming. The automated programming results in CNC programmes with minimum interventions of the human, particularly for the geometries consisting of basic geometrical features. The role of the human-programmer is limited only to entering of input data and teaching of the system. The paper defines the areas of development of the CAM programme crucial for the development of such programming. On the basis of those development areas the automated programming system together with integral parts is presented. The use of such system will not only increase the productivity of programming, but will also change the use of numerically controlled machines from organizational and technical aspects.

Key Words: CNC programming, Automated programming, CAM

1. INTRODUCTION

All users of the CNC machines desire the creation of CNC programme to be fast and to require little resources and capacities. The creators of CAM programmes meet these desires by the fast development cycle gradually introducing more and more efficient tools. Systems for automated programming, most frequently in the form of complements to CAM programming have started to appear on the market. Although those systems have rather limited capacities, their applicability is on the increase. There are many shapes not needing advanced programming techniques. If we look at the sheet steel forming tool, which is very complex, it can be seen that only a few elements are of exacting sculptured shapes, whereas the other parts are mostly composed of the basic geometrical components. Creation of CNC programmes for machining of such parts can be partly left to automated programming. Thus, the companies already appear using the systems for automated programming [1], [2], [3]. The reason of starting to use those systems is usually the specific production process and the sense of such technology on the part of the managing personnel. In the custom production of geometrically similar products, where a new CNC programme would be necessary for each product, the automated programming brings great benefits compensating the investment into such system.

In the first part the paper presents the evolution of CNC programming since the beginning till today, and then it defines the trends in the development of CAM programmes and the needs of users of CNC machines in the future. The third part indicates the areas on which the success of automated programming depends.

2. DEVELOPMENT OF PROGRAMMING OF CNC MACHINES

Soon after John T. Parsons in early fifties had developed a numerically controlled machine [4], the need for efficient programming emerged. For that reason and because of the development of the numerical control technology of machine tools several programming methods emerged.

2.1 Manual programming

In the sixties and seventies of the preceding century in most cases manual programming sufficed in the industrial practice. Due to limitations of the human mind such type of programming does not make use of all possibilities of the numerically controlled machine. If certain capabilities of the human are compared with similar capabilities of the computer, it can be established that the computer surpasses the human in quite a few respects. However, the human brain has the capabilities, such as efficient recognition of samples, good organization of knowledge and capable searching for knowledge. Therefore, the computer started early to be used for creation of CNC programmes. Higher programme languages were developed, the most widespread being APT [5], [6], which ensured the entering of the product geometry. Those programme languages relieved the human only in repeating operations. Manual programming is not suitable for programming geometrically sophisticated shapes and today it is often too exacting and too slow even for relatively simple shapes [7], [8]. Therefore, it is less and less used, but it can not be claimed that it is disappearing. It must be borne in mind that the computer-supported programming proceeds from the manual programming and applies the approaches based on manual programming. Thus, the familiarization with manual programming is still always important for good use of the CAM programme [9].

2.2 Workshop programming

Since the beginning of the commercial use of numerically controlled machines it has been possible to program also on the machine itself. The controls always ensure manual operating of the machine along coordinates and often also more advanced programming in the higher-level programme language inherent in the controls. Some authors claim that such type of programming belongs to manual programming [10]. However, special attention must be paid to programming on the machine, since it has developed and persisted till today, while the conventional manual programming has practically disappeared and/or has been transformed into programming on the machine. As programming on the machine has every characteristic of manual programming, a more suitable term for it might be manual programming on the machine.

Programming on the machine and/or workshop programming, similarly as the manual programming, gradually started to acquire more complex commands and functions, supported in the machine controls. Those functions include, particularly, the machining cycles, the repeating operations and the operations executed according to the sample and logical operations [9]. However, these advanced capabilities of the controls are not very applicable, particularly, due to the difficulties in communication and interaction between machine and human. Further, the level of knowledge required for utilization of the capabilities of controls is too high for machine operators. Moreover, the productivity of such programming is low, since it does not considerably exceed the productivity of manual programming. Anyhow, the human is the principal performer of the computing operations and, in the same time, the limiting factor. Such type of programming of machines is largely used for machining simple parts in custom production. Programming on the machine eliminates the need for the programmer and for computer-supported technologies, thus reducing the costs and facilitating the organization. On the other hand, by using the programming on the machine, the benefits of the available modern technologies are given up.

2.3 CAM

With the development of the hardware and software the manual programming by means of the computer gradually progressed to computer-aided manufacture. At first, those systems mastered only the geometrical part of programming. Though the term CAM comprises fairly more than only computer-aided programming of machines, this paper will be focussed only on this CAM function. The beginnings of the CAM reach back to the seventies, i.e., to the time of the programme language APT and Compact II, but the development became appreciated only in the eighties of the previous century. The computer technology advanced, graphic interfaces ensuring intuitive and interactive entering of geometry were presented. The three-dimensional CAD models became the principal carriers of information about the product. The fast development of the technology led from wire CAD models to 3D solid models. In the nineties that development proceeded so far that the personal computers became the principal aid of designers and CNC programmers [11]. The surface and solid models and the 3D accelerated shaded computer graphics with high resolution came into use. The development of CAD models was followed by the development of CAM programmes making use beneficially of the increasingly accurate and comprehensive geometrical information from the CAD model. Due to growing applicability of CAM programmes and accessibility of platforms for driving those programmes, the CAM programmes became very widely used by the programmers of CNC machines.

Creation of CNC programmes by the CAM software became irreplaceable, particularly for complex workpieces and/or sculptured shapes. With the expansion of the application area of CNC machine also into the field of custom production, the need for productivity and simplicity of the CAM software increased. The users of CAM programmes must be highly qualified and experienced experts combining the technological know-how and the programming knowledge.

3. NEED FOR AUTOMATED PROGRAMMING

3.1 Where is automated programming needed?

Today, practically all CNC programmes are created in two ways; i.e., by manual programming executed mainly on the machine and by CAM applications taking over the major part of process of creation of CNC programmes. These two manners of programming can be distinguished as to where the programme is formed and as to what technical means are used to that end. On the one side there is the capable and demanding programming by CAM programmes affected in the office and on the other side there is the relatively simple and time-consuming programming on the machine:

- CAM supported programming applicable for programming of the most complex CNC machines and the most exacting machining operations. The programming is exacting, it requires highly qualified programmers-technologists. They must posses in addition to programming skills, also the technological knowledge and experience. For programming the CAD model of the product and blank is needed.
- Programming on the machine (control). It is applicable for programming of manufacturing of simple shapes, particularly in custom or small-series production. It is largely used in the workshop use of CNC machines. Programming can be affected by the machine operator with relatively little knowledge; he must have the technological knowledge and experience. CAD models are not needed. Its deficiencies are low productivity, the machine is occupied during programming, lots of defects resulting from the human factor.

Figure 1 shows the use of technical resources (computer) for the individual kinds of programming. In case of CAM and programming on the machine the computing operations are executed by computer and only partly by the human. However, there is an important difference between both methods of programming; in case of CAM the computing operations are executed by the external computer (most frequently, personal computer) and in case of programming on the machine the computing operations are executed by the computer in the control. Though there are less and less differences between the external (personal) computers and the computers in the controls from the mechanical aspect, there is still always a significant difference in the purpose of their use. The external computers are much more adaptable, they feature wide applicability and good capacities of interaction between the computer and the human. On the other hand, the integrated computers are primarily the control units serving in the first place for the machine control. The personal computers are oriented to the human, while the control computers are oriented to the machine.

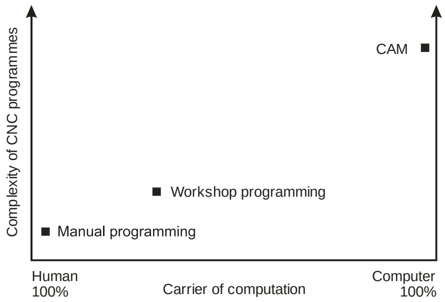

Figure 1: General division of methods of programming as to by whom the computing operations are executed.

Due to the deficiencies of CAM programming, already mentioned, the users need a system which is simple for use such as programming on the machine and which makes use of the benefits of CAM programming. It can be seen that those two methods of programming complement themselves in the purpose and properties as shown in Figure 2. For simple, particularly 2D and 2,5D products, especially in the custom workshop production the programming on the machine is often used. For more exacting shapes the CAM programming is used. However, the programming on the machine is less and less competitive.

Programming on the machine does not belong to the CAx chain of technologies. Nowadays, from conceiving to managing of the life cycle of the product the CAD models are used. Thus, during manufacture of the product the CAD model and/or all components of the product are at hand. With the exit from the CAx chain in the manufacture the potentials, assured by modern technologies in this area such as simulation of cutting, simulation of the machine and optimization, are abandoned.

Due to the modern CAx support to the manufacture, the opportunity to meet the need for a new programming method, combining the benefits of manual of CAM programming, has appeared. What is needed is a highly automated programming, simple for use and suitable particularly for simple problems. Simple problems are meant to be technologically non-exacting machining operations, particularly on the products built from geometrical features. Automated programming will assure high productivity in creation of programmes and will eliminate the need for highly qualified personnel for programming of CNC machine tools. This new method of creation of programmes will require very few interventions and decisions from the human.

Figure 2 shows the area of application of automated programming with respect to exactingness and extent of the problem. By manual programming it is not possible to prepare CNC programmes for complex products, though they consist of simple geometrical features. This is caused by the exactingness and/or extent of the problem. The CAM programming can manage all areas, but it is not very competitive and applicable in the whole area. For organizational and economic reasons the CAM programming is not very suitable for the simplest cases. In fact, nowadays all CNC programmes, except the simplest ones, are created by CAM programmes. Automated programming will reduce the application area of the CAM programming and will almost totally suppress manual programming.

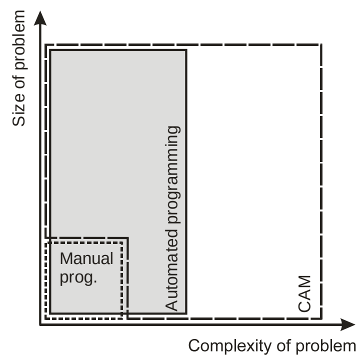

Figure 2: Area of use of conventional and automated programming.

3.1 Expectations of users

In 2005 the conference "Manufacturing vision", organized and financed by the European commission, discussed the development orientations in the field of manufacture. By a questionnaire survey, experts were enquired about the need for selected technologies in development. Also the expectations of users and the time frameworks, within which the users expect the selected technology to become established, were verified. It was found out that, in the field of machining, the experts expected most of the automated programming of CNC machines. Only a little less than 10% of those surveyed ascribe smaller importance to the development of automated programming (Figure 3). In addition, almost 70% of those surveyed expect that the automated programming will be introduced into practice within the next ten years (Figure 3).

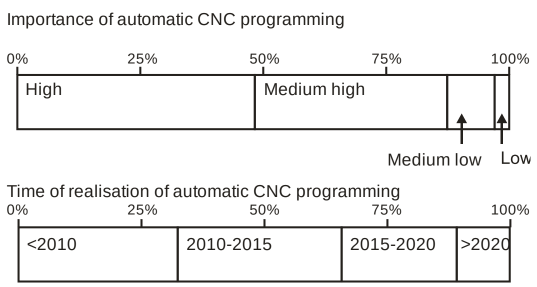

Figure 3: Importance for industry and expected time of realisation of automatic CNC programming (adopted from [12]).

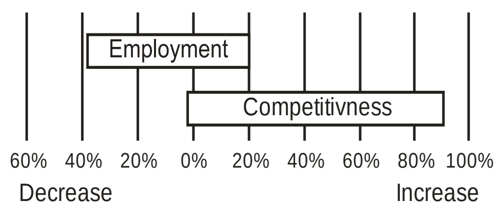

Figure 4: Expected effects of automated programming.

Similarly, much is expected also of improved simulations and/or virtual machines [12] in the machine controls. Also the time frame, within which the virtual machine is expected to be created, is similar. Automated programming of CNC machines is associated with the implementation of virtual machines, since due to absence of the expert's evaluation of the programming results a system for reliable evaluation of quality of the CNC programmes is needed. Experts expect, particularly, the increase of competitiveness of the automated programming of CNC machines (Figure 4). Like everywhere, where the degree of automation of processes is increased, also here the introduction of automated programming increases the productivity and reduces the need for human resources, engaged in the manufacture.

When implementing the automated programming, the users anticipate most difficulties in searching for technical solutions as shown in Figure 5. As there are not yet any wide-spread solutions on the market, it is understandable that the users do not yet see the solution. Experts anticipate difficulties also in the area of education and difficulties due to shortage of finances for the development (Figure 5).

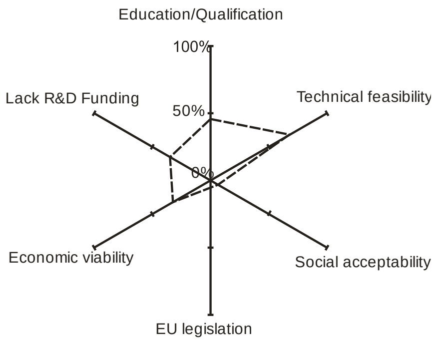

Figure 5: Anticipation of difficulties in introducing automated programming (adopted from [12]).

Users are aware of the applicability of automated programming and the necessity of development and, later on, the use of the automated programming technology in order to reach higher productivity and competitiveness in the future. Though the users mostly do not doubt the advent of automated programming, they are aware, particularly, of the technical and organizational difficulties, which must be overcome to ensure the use of automated programming in the future.

3.3 CNC programmer's role

Since the beginnings of use of the CNC machines the role of the CNC programmer has changed very much. In case of manual programming the programmers carried out the totality of the programming activities by own brain capacities. First, the computers replaced the human brain in repeating operations. Later on, they took over a large part of the computing operations for the determination of the tool path, but all the same the human had to affect entering of the shape and determining of the technological parameters. Gradually, the CAM applications took over more brain work from the human and forced the programmer, particularly, into the role of technologist/strategist using his technological knowledge and experience and the knowledge of use of the CAM programme.

Contrary to early CNC programmers the programmers today do not need much mathematical and geometrical knowledge. The CNC programmers fill the gaps of the technological knowledge, which the CAM programmes can not fill. Those gaps result from the incomplete definition of the final product in the CAD model [13], [14], [15], [16] and from the fact that the CAM programmes are not able to capture technological experience and knowledge. Since the human is very efficient in filling those gaps, it can be expected that the need for CNC programmers will persist still a fairly long time. Today, programmers are responsible for high-quality and effective utilization of CNC machine tools.

In addition to the technological knowledge and experience the CNC programmers must be familiar with handling of CAM applications. The purpose of automated programming is to avoid the need for such knowledge. It is desirable that programming should become so simple that CNC programmers would only fill the gaps in the software capacities, whereas the repeating operations in programming would be taken over by the software. The system for automated programming reduces the need for the computer knowledge of users and for the knowledge of handling of CAM programmes. The use of such system will ensure the introduction of the real workshop programming, when the machine operator prepares the programme immediately before machining.

4. CONCLUSION

Switching over to geometrical modelling of solid bodies with the use of geometrical features has ensured the use of more advanced techniques of creation of CNC programmes and increasing automation of programming. The CAM programmes develop in the direction of automated programming. The use of this technology will not only facilitate programming, but will redefine the concept of work with CNC machines. Due to simplified creation of CNC programmes those machines will become more usable and more adaptable; shortly, they will become more applicable in the conventional concept of workshop production.

Nevertheless, it is necessary to bear in mind that automated programming is only at the outset. Efficient automated programming will require the use of intelligent methods which will partly replace the need for the human intellect. For the time being, the existing applications of automated programming are limited to the characteristic classes of products which are built from the most basic geometrical features and have similar topography. For the time being the applicability is limited, but in some manufacturing branches it suffices.

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