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# Performance evaluation of factors affecting cutting forces on CNC Milling using Digraph and Matrix method

Mandeep Chahal[1], Sandeep Malik[2]

[1]*Asst. Professor at Department of Mechanical Engineering, HCTM, Kaithal, Haryana, India*
[2]*Student at HCTM, Kaithal, Haryana, India*

**Abstract-** Machinability aspect is of considerable importance for efficient process planning in manufacturing. Machinability of an engineering material may be evaluated in terms of the process output variables like material removal rate, processed surface finish, cutting forces, tool life, specific power consumption, etc. In this paper, graph theoretic approach (GTA) is proposed to evaluate the cutting force during CNC milling. Cutting force is considered as a machinability attribute during CNC milling to evaluate the effect of several factors and their subfactors. Factors affecting the cutting force and their interactions are analyzed by developing a mathematical model using digraph and matrix method. Permanent function or machinability index is obtained from the matrix model developed from the digraphs. This index value helps in quantifying the influence of considered factors on cutting force. In the present illustration, factors affecting cutting force during CNC milling are grouped into five broad factors namely work material, machine tool, cutter runout, penetration strategies, and tool geometry to be machined. GTA methodology reveals that the machine tool has highest index value. Therefore, it is the most influencing factor affecting cutting force.

**Keywords-** Graph theory, Index value, CNC Milling, Cutting Force

## 1. INTRODUCTION

Quality of manufactured product depends on umpteen numbers of factors which may be interdependent in nature. Among them, machinability of work materials is a crucial factor which may affect the different manufacturing phases including product design, process planning, machining operations, etc. Therefore, machinability aspect of work materials is of substantial importance for efficient process planning (Jangra et al. 2002). Machinability is also function of various input variables such as the inherent properties of work material, machining method, cutting tool material, tool geometry, the nature of tool engagement with the work material, cutting conditions, type of cutting, cutting fluid, machine tool rigidity, and its capacity (Rao and Gandhi 2002).

Furthermore, it has been observed that the improvement in the output variables, such as tool life, cutting forces, surface roughness (SR), etc., through the optimization of input parameters, such as feed rate, cutting speed and depth of cut, may result in a significant economical performance of machining operations (Kadirgama et al. 2007). As a basic machining process, milling is one of the most widely used metal removal processes in industry and milled surfaces are principally used to mate with other parts in die, aerospace, automotive, and machinery design as well as in manufacturing industries (Altintas 1994).

CNC Milling system serve as an alternative to EDM for making dies or moulds from the hardened tool steels. It produces the die faster and is also more accurate, because fewer steps result in reduced error stacking. It can result in significantly lower manufacturing costs and times when compared with existing production processes and its performance is characterized by a lot of the machining factors. Any modifications may lead to significant consequences on the machining performances. End milling is the widely used operation for metal removal in a variety of manufacturing industries including the automobile and aerospace sector where quality is an important factor in the production of slots, pockets and moulds/dies (Mike et al, 1999; John and Joseph, 2001). The quality of surface is of great importance in the functional behavior of the milled components. Liao and Lin (2007) studied the milling process of P20 steel with MQL lubrication.
The use of computer numerical control (CNC) machining centers has expanded rapidly through the years. A great advantage of the CNC machining center is that it reduces the skill requirements of machine operators. One of the most important yet least understood operation parameters of a machining operation is the cutting force. In general, this force is thought of as a 3D vector that is represented by three components, namely, the power component, the radial component and the axial component in the tool coordinate system (Zorev, 1966). Of these three components, the greatest normally is the power component, which is often called the cutting force. This simplification will be used through the body of this paper. As this

force is of high importance, one might think that theoretical and experimental methods for its determination have been developed and are thus available in the literature. Unfortunately, this is not the case. When it comes to a possibility of theoretical determination, the foundation of the force and energy calculations in metal cutting is based upon the over simplified orthogonal force model known as Merchant's force circle diagram or a condensed force diagram (Komanduri, 1993; Merchant,2003).

Thus, much effort has been devoted to developing indirect force-measurement tools. Various mechanical or electrical variables of feed- and spindle system conditions have been studied to estimate forces. For spindle systems, Shuaib et al. installed a strain gauge between the spindle axis and the tool, and then measured cutting torque. It is advantageous to measure the cutting force at a spindle because it is close to the cutting point. However, complexity of spindle integration is problematic. When it comes to experimental determination of the cutting force, there are at least two problems.

1. First and foremost is that the cutting force cannot be measured with reasonable accuracy although this fact has never been honestly admitted by the specialists in this field. To appreciate the issue, one should consider the results of the joint program conducted by The International Academy for Production Engineering, and National Institute of Standards and Technology (NIST) to measure the cutting force in the simplest case of orthogonal cutting (Ivester, 2004). The experiments were carefully prepared (the same batches of the workpiece (steel AISI 1045), tools, etc.) under the supervision of National Institute of Standards and Technology (NIST) and replicated at four different most advanced metal cutting laboratories in the world. Interestingly, although extraordinary care was taken while performing these experiments, there was significant variation (up to 50%) in the measured cutting force across these four laboratories. If less care is taken and no laboratory conditions are available then the accuracy of cutting force measurement be much would worse.
2. Second, many tool and cutting inserts manufacturers do not have adequate dynamometric equipment to measure the cutting force. Many dynamometers used in this field are not properly calibrated because the known literature sources did not present proper experimental methodology for cutting force measurements using piezoelectric dynamometers (Astakhov and Shvets, 2001).

In recent times, computer numerically controlled (CNC) machine tools have been implemented to realize full automation in machining (Kalpakjian & Stevan 2000; Rao 2001; Bhattacharyya 2006; Grover 2007). CNC machine tools provide greater improvements in productivity, and increase the quality of the machined parts and require less operator input. Out of the various CNC industrial machining processes, milling is one of the vital machining operations. Milling is a common metal removal operation in industry because of its ability to remove material faster with a reasonably good surface quality.

It is widely used in a variety of manufacturing industries including aerospace and automotive sectors, where quality is an important factor in the production of slots, pockets, precision moulds and dies. Tsai et al (1999) studied the effect of spindle speed, feed rate and depth of cut on surface roughness in end milling of 6061-T6 aluminum. If milling conditions are not selected properly, the process may result in violations of machine limitations and part quality, or reduced productivity. The cutting forces affect the quality and the precision of the final component; therefore precise prediction of milling forces becomes an important factor to improve machining performance. Moreover, reliable quantitative prediction of cutting forces is essential for further prediction of the necessary power and torque, machine tool vibrations, work piece surface quality, geometrical accuracy and process stability. Cutting forces provides a basis for surface accuracy prediction and improvement, tool wear rate, the energy consumption within the machine tool, depending on power consumption and operating time.

A number of approaches and methodologies developed by researchers are available in the literature to model the various systems and their elements. Graph theory is one of such methodologies. It synthesizes the inter-relationship among different parameters and systems to evaluate score for the entire system. Because of its inherent simplicity, graph theory and matrix method have wide range of applications in engineering, science and in numerous other areas. Several examples of its use have appeared in the literature to model the various systems. Graph theory is a logical approach that has been applied in various fields of science and technology (Grover et al. 2004; Jangra et al. 2010; Rao and Padmanabhan 2006; Venkatasamy and Agarwal 1995; Mohan et al. 2003). The matrix approach is useful in analyzing the graph models expeditiously to derive the system function and index to meet the objectives. Moreover, representation of graph by a matrix offers ease in computer processing (Jangra et al. 2002). This paper reveals the utilization of graph theoretic approach (GTA) to determine the factors affecting cutting force with CNC Milling. Various factors, sub-factors and their interdependencies that affect the cutting force is prepared by a digraph and demonstrated by a matrix. A numeric value named as index value (MI) has been calculated to evaluate the cutting force. A detailed literature review has been done to determine the various factors and sub-factors that affect the cutting force under different machining methods. Experimental results and the methodology based on graph theory to evaluate the Index value have been discussed in the later sections.

## 2 LITERATURE REVIEW AND IDENTIFICATION OF FACTORS AND SUB-FACTORS IMPACTING CUTTING FORCE

In order to achieve the objectives of this research a literature review was conducted. The literature involved information on Graph theory and Matrix method used in various field of science and technology and also on the behavior of cutting force during machining.

Lou et al. (1999) carried out experimentation to evaluate that feed rate was the most significant machining parameter used to predict the SR in the multiple regression models. Tsai and Chen(1999) stated that as a multi-point machining process, more potential variability makes it even harder to obtain a SR model in milling operations compared with single point machining and the possible factors affecting surface finish were found to be feed rate, cutting speed, depth of cut, cutter geometry, cutter run out, tool wear, and the cutter force and vibration under dynamic cutting conditions. Toh (2006) investigated and evaluated the different cutter path orientations when high-speed finish milling hardened steel, and the results demonstrated that vertical upward orientation has been generally preferred in terms of workpiece SR.

Zhang et al. (2007) suggested that Milling has been one of the most widely used metal removal processes in industry and milled surfaces are largely used to mate with other parts in die, aerospace, automotive and machinery design as well as in manufacturing industries. Heinz A Preisig (2007) Suggested A Graph-Theory-Base Approach to the Analysis of Large-Scale Plants On-line balancing of mass and energy in a large-scale plant is a feasible operation given the development state of the current data-acquisition systems. However, not all data are available in real time and the programmed version of the instrumentation flow sheets in form of a graph cannot be used directly. They need to be modified so as to match the available information. Two cases are discussed: the dynamic case, where all units are seen as dynamic components and the steady state case, where each unit is assumed to operate at steady state. The analysis is done purely on a graph basis. The idea is the essential part; the resulting algorithms are extremely simple and only require a path search algorithm such as depth-first or a breath-first search algorithm.

Gologlu and Sakarya (2008) studied that Milling of machining parts could be accomplished by employing different cutter path strategies (step over), which were one direction, back and forth and spiral cutter path strategies. Viktor P. Astakhov and Xinran Xiao (2008) Provide a methodology for practical cutting force evaluation based on the energy spent in the cutting system. This paper presents a methodology for practical estimation of cutting force and cutting power. This paper provides a complete list of mathematical expressions needed for the calculation of each energy mode and demonstrates their utility for turning operation of two work materials: AISI bearing steel E52100 and aerospace aluminum alloy 2024 T6. The calculated cutting forces were in fairly good agreement with the experimental results.

Ding et al. (2010) experimentally investigated the effects of cutting parameters on cutting forces. carbide tools and empirical models for cutting forces and SR in hard milling of AISI H13 steel with coated established. The analysis results showed that finish hard milling can be an alternative to grinding process in the die and mold industry. Hasan Gökkaya (2010). Suggested The Effects of Machining Parameters on Cutting Forces, Surface Roughness, Built-Up Edge (BUE) and Built-Up Layer (BUL) During Machining AA2014 (T4) Alloy. Tool wear, formed in cutting tool during machining processes, affects the surface roughness of the work piece, cutting forces and other output parameters. The effects of the machining parameters cutting speed (Vc) and the feed rate (f) on built-up edge (BUE), built-up layer (BUL), main cutting force (Fc), and surface roughness (Ra) is investigated in this study.

Yunwen Sun and Qiang Guo (2011). Provide a Numerical simulation and prediction of cutting forces in five-axis milling processes with cutter run-out. Radial cutter runout is a common issue in milling processes and has a direct effect on milling stability due to variations of resulting chip load and forces. This paper presents a new method to effectively model and predict the instantaneous cutting forces in 5-axis milling processes with radial cutter runout based on tool motion analysis. U. Zuperl et al.(2011) Provide a Neural control strategy of constant cutting force system in end milling. This paper discusses the application of neural adaptive control strategy to the problem of cutting force control in high speed end milling operations. The research is concerned with integrating adaptive control and a standard computer numerical controller (CNC) for optimizing a metal-cutting process.

Huang et al. (2012) developed a hybrid graph theory and GA approach to process planning for a prismatic part within the context of CAPP. In this approach, operations and the precedence constraints among all the operations were formulated in an operation precedence graph (OPG), the decision making of selecting alternative manufacturing resources and tool approach direction (TAD) for every operation, determining in what order to perform a set of selected operations such that the resulting sequence satisfies the precedence constraints established by both features and operations, could be considered concurrently to achieve the optimal plan. Jaime Cerda Jacobo et al. (2012) provide A Graph-based Method to Solve the Economical Dispatch Problem Disregarding Slack Variables One of the greatest challenges to confront Nonlinear Programming Problems; it is the selection of the active and non active set of constraints of the system.

Srishti Sabharwal and Suresh Garg(2013). Determining cost effectiveness index of remanufacturing: A graph theoretic approach Remanufacturing is a powerful product recovery option which generates products as good as new ones, from old discarded ones. Growing concern for energy conservation and waste reduction led to the augmentation of this technique. However, like any other business, remanufacturing also considers cost saving as an important aspect before it can be adopted in any industry. Rajesh Attri and Sandeep Grover (2013). Application of preference selection index method for decision making over the design stage of production system life cycle The life cycle of production system shows the progress of production system from the inception to the termination of the system. During each stage, mainly in the design stage, certain strategic decisions have to be taken.

Vinay Babu Gada et al. (2013) In the present study, an attempt has been made to investigate the effect of primary cutting parameters (cutting speed, feed and depth of cut) and tool overhang length on cutting forces and chatter starting point lengths in finish turning of EN8 steel, EN24 steel, Mild steel and aluminium. Machining test cuts are conducted using sharp tool and the effect of cutting conditions and tool overhang length are also studied. Here experiments are conducted on four work piece materials at different cutting parameters and different overhang lengths. The chatter starting point is measured from the free edge of the work piece and graphs were plotted between overhang length verses cutting forces and chatter staring point lengths. Renjith V B et al. (2013). Concluded Deflection of cutting tools during machining on a lathe affects their tool life, surface roughness and dimensional correctness. For an optimum turning operation, correct selection of cutting parameters as well as tool extension length are essential. In this work, deflection of a T-42 CT H.S.S single point cutting tool is investigated by varying rake angle, cutting feed and tool extension length during turning operation on lathe. The selection of process parameters were determined by using Taguchi‘s experimental design method. Cutting force components during turning operation were measured by lathe tool force dynamometer and detailed deflection analysis was conducted by using ABAQUS finite element program.

Nikhil Dev et. al (2014). Provide A systematic approach based on graph theory and matrix method was developed ingeniously for the evaluation of reliability index for a Combined Cycle Power Plant (CCPP). In present work CCPP system is divided into six subsystems. Consideration of all these subsystems and their interrelations are rudiment in evaluating the index. Reliability of CCPP is modelled in terms of a Reliability Attributes Digraph. Nodes in digraph represent system reliability and reliability of interrelations is represented by edges. The digraph is converted into one-to-one matrix called as Variable System Reliability Permanent Matrix (VPM-r). Dong-Hyeon Kim and Choon-Man Lee(2014). Was conduct a study of cutting force and preheating-temperature prediction for laser-assisted milling of Inconel 718 and AISI 1045 steel. Laser-assisted machining involves machining a workpiece after softening it with laser-emitted heat.

Vishal S. Sharma et al. (2014) were Investigated the tool geometry effect and penetration strategies on cutting forces during thread milling. The application of thread milling is increasing in industry because of its inherent advantages over other thread cutting techniques. The objective of this study is to investigate the effect of milling cutter tool geometry on cutting forces during thread milling. The proposed method can compare the performance of milling cutters in spite of the different number of tooth. The best thread milling cutter among the studied tools was determined from the cutting forces point of view. Furthermore, this study also pinpoints the best penetration strategy that provides minimum cutting forces. Lower cutting force variations will lead to fewer vibrations of the tool which in turn will produce accurate part.

Based on the detailed literature related to the machining of tool steels and other hard materials, various factors and sub-factors have been identified which affect the cutting force during machining with CNC Milling. Table1 summarize these factors and sub-factors.

## Problem Identification

1. Literature review reveals that researchers have carried out most of the work with AHP (analytic hierarchy process), ANN (artificial neural network), DOE (design of experiment), Taguchi method and RSM (Response surface methodology) but very limited work has been reported with Graph theory and Matrix approach.
2. Very limited work has been reported to evaluate the cutting force on CNC Milling by using graph theory and matrix approach.
3. Most of the researchers have applied Graph Theory to evaluate the surface roughness and MRR. Here I am applying Graph Theory to evaluate cutting force during CNC Milling.

## 3 GRAPH THEORY AND MATRIX APPROACH

The beginning of Graph theory is said to have in 1736 when EULER considered the Konigsberg bridge problem. Subsequently, the graph theory has been applied in various fields of engineering such as physics, chemistry, mathematics, electrical engineering, sociology, computer technology (net working), economics, operation research, etc.

Graph theoretic approach (GTA) is a systematic methodology for conversion of qualitative factors to quantitative values and mathematical modeling gives an edge to the proposed technique over conventional methods like cause-effect diagrams, flow charts etc. Graph theory serves as a mathematical model of any system that includes multi relations among its constituent elements because of its diagrammatic representations and aesthetic aspects. GTA is a three stage unified systems approach (Deb, 2000).

(i). Modeling of systems in terms of nodes and edges gives a structural representation to the system and results in a directed graph. This representation is suitable for visual analysis and understanding the interrelationships among various nodes.
(ii). For further analysis, digraph representation is converted to matrix form, which makes it suitable for computer processing. However the matrix representation is not unique as changing the labeling of nodes can change it.

(iii). Analysis of matrix model results in permanent function model, which is in the expression form. The permanent function model analyzes various combinations among the factors and interrelationships. Simplified permanent function expression is represented in terms of a single numerical index.

Using graph theoretic approach, several attempts have been made to solve the industrial problems involving multi variables having interaction among them (Wani and Gandhi, 1999; Rao and Gandhi, 2002, 2006; Grover et al., 2004; Jangra et al., 2011).

### 3.1 Objectives of Study

Graph theory is a logical and systematic approach. The advanced theory of graphs and its applications are very well documented. Rao (2007) in his book presents this methodology and shows some of its applications. Graph/digraph model representations have proved to be useful for modeling and analyzing various kinds of systems and problems in numerous fields of science and technology. The matrix approach is useful in analyzing the graph/digraph models expeditiously to derive the system function and index to meet the objectives.

The graph theory and matrix methods consist of the digraph representation, the matrix representation and the permanent function representation. The digraph is the visual representation of the variables and their interdependencies. The matrix converts the digraph into mathematical form and the permanent function is a mathematical representation that helps to determine the numerical index.

### 3.2 Methodology

The various steps involved in graph theoretic approach are enlisted in sequential manner as below:

1.Identify the various sub-systems affecting the main system.

2.Logically develop a diagraph between the system/sub-system depending upon their interdependencies.

3. Develop a variable permanent function matrix at the sub-system level on the basis of digraph developed in step 2. Matrix representation of the alternative selection criteria digraph gives one-to-one representation. A matrix called the equipment selection criteria matrix. This is an M in M matrix and considers all of the criteria (i.e. $A_i$) and their relative importance (i.e. $a_{ij}$). Where $A_i$ is the value of the i-th criteria represented by node $n_i$ and $a_{ij}$ is the relative importance of the i-th criteria over the j-th represented by the edge $e_{ij}$ (Rao, 2007; Faisal et al., 2007).

The value of $A_i$ should preferably be obtained from available or estimated data. When quantitative values of the criteria are available, normalized values of a criterion assigned to the alternatives are calculated by $v_i/v_j$, where $v_i$ is the measure of the criterion for the i-th alternative and $v_j$ is the measure of the criterion for the j-th alternative which has a higher measure of the criterion among the considered alternatives. This ratio is valid for beneficial criteria only. A beneficial criteria means its higher measures are more desirable for the given application. Whereas, the non-beneficial criterion is the one whose lower measures are desirable and the normalized values assigned to the alternatives are calculated by $v_j/v_i$.

$$CS\ \text{Matrix} = \begin{bmatrix} A_1 & a_{12} & a_{13} & a & a & a_{1.m} \\ a_{21} & A_2 & a_{23} & \cdots & \cdots & a_{2.m} \\ a_{31} & a_{32} & A_3 & \cdots & \cdots & a_{3.m} \\ \vdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \vdots & \ddots & \cdots & \cdots & \cdots & \vdots \\ a_1 & a_1 & a_1 & \cdots & \cdots & A_m \end{bmatrix}$$

4.Using the logical values of the inheritances and interdependencies, obtain the permanent functions at the system/subsystem level. The off- diagonal elements of the matrix representation may be obtained from the graphs, knowledge database interpretation or from the excerpts of the expert's opinion.

5. Evaluate the permanent of the variable permanent function at the system/sub-system level. Obtaining alternative selection criteria function for the matrix. The permanent of this matrix, is defined as the alternative selection criteria function.

**3.3 Implementation**

Graph/digraph model representations have proved to be useful for modeling and analyzing various kinds of systems and problems in numerous fields of science and technology. GTA is a systematic and logical approach which synthesizes the interrelationship among different parameters or sub-system parameters and provides a synthetic score for the entire system.
It also takes care of directional relationship and interdependence among parameters. The graph theoretical methodology consists of three steps namely – digraph representation, matrix representation and permanent function representation.

A digraph is used to represent the structure of the system in terms of nodes and edges where in the nodes represent the measure of characteristics and the edges correspond to dependence of characteristics. Matrix representation is one to one representation of the digraph. Permanent representation is the mathematical expression of characteristics and their interdependence. Digraph representation, matrix representation and permanent function are developed for the quality, cost, reliability and efficiency characteristics.

**Digraph representation:** A digraph is basically a directed graph that demonstrates the factors affecting cutting force and their interdependence in terms of directed edges. In this research, work material (A1), cutter runout (A2), tool geometry (A3), penetration strategies (A4) and machine tool (A5) are selected as factors which affect the cutting force. Machine tool affects the work material, cutter runout, tool specification and penetration strategies so directed edges have been drawn from A5 to A1, A2, A3 and A4. Work material also affects all the other 4 factors, hence directed edges from A1 have been drawn to A2, A3, A4 and A5. Similarly directed edges for A3–A5 are drawn and the inter-relationship between factors can be represented by Fig.1.

**Matrix Representation:** Digraph presentation is very suitable for visual analysis but is not very suitable for computer processing. Moreover if the system is large, its corresponding graph is complex and this complicates its understanding visually. In view of this, it is necessary to develop a representation of the digraph that can be understood, stored, retrieved and processed by the computer in an efficient manner. Many matrix representations for example adjacency and incidence matrix available in literature2,3 to model the graph mathematically. The adjacency matrix is a square matrix and is selected for this purpose. It being a matrix and multinomial has been derived subsequently based on connectivity only, neglecting the directional properties.

**Permanent Representation:** Both digraph and matrix representations are not unique in nature because they are altered by changing the labels of their nodes. Hence, to develop a unique representation that is independent of labeling, a permanent function of the system matrix is proposed here. The permanent is a standard matrix function and is used in combinatorial mathematics. The permanent function is obtained in a similar manner as the determinant but unlike in a determinant where a negative sign appears in the calculation, in a variable permanent function positive signs replace these negative signs.

**3.4 Application of Graph theory**

Application of graph theory has been widely spread into various fields of science and technology.

1.Venkatasamy and Aggrawal (1995) applied graph theoretical approach to evaluate and analyze the quality of the automotive vehicle by considering the characteristics of the vehicle. Twelve quality characteristics of a vehicle were identified. The various factors that affect these characteristics were also identified. Digraph representation, matrix representation and permanent function were developed for the quality characteristics. Evaluation of vehicles was given in terms of vehicle quality index, which can be used to compare and rank vehicles in particular type.

2.Rao and Gandhi (2002) analyzed the failure causes of a machine tool using digraph and matrix methods. To develop machine tool failure casualty digraph, a machine tool failure cause, vibrations of a machine tool, was considered. Six important contributing events; machine tool leveling, type of cutting and cutting conditions, in homogenities in the work material, disturbance in machine tool drives, cutting process and tool setting and job handling were analyzed. R.Venkata Rao, O.P. Gandhi (2002) proposed a methodology which is used for selecting the best work-tool combination for a given machining operation. Unlike conventional methods which adopt only one of the machinability assessment criteria, the proposed method considers all the criteria simultaneously & gives the correct and complete evaluation of the machinability of work materials. The proposed universal machinability index evaluates and ranks work materials for the given machining operation.

3.Grover et al. (2004) used the digraph approach to evaluate the total quality management (TQM) environment of an industry. A mathematical model was developed for TQM environment by considering the several factors. These factors were broadly grouped into behavioral factors, non-behavioral factors, use of tools and techniques, human factors and functional factors. Numerical value was evaluated as a TQM index which is useful for comparison, ranking and optimum selection. In another paper Grover et al. (2006) presented digraph and matrix approach for evaluation of extent of human aspects present in an organization. The 'human factors' in total quality management (TQM) environment was determined in terms of a single numerical index by considering their inheritances and interactions. In this paper, interaction among identified human factors is represented through digraph, matrix model and a multinomial.

4.Mohan et al. (2005) developed a mathematical model using graph theory and matrix method to evaluate the performance of a steam power plant. For developing a system structure graph, sub-systems for boiler viz. air system, water system, combustion chamber/furnace, flue gas system and superheated steam system and their interactions were considered. The methodology converts a real life steam power plant into a block representation and then to a graph theoretic representation. The permanent function of the boiler system at a particular level of hierarchy represents all possible combinations of its subsystems.

5.Sushma Kulkarni (2005) introduced a methodology in graph theoretic approach to evaluate the performance index and ranks the various industries practicing TQM for a given time. To identify and compare various TQM performances in industry, performance index is to be used. This approach presents a rank to different industries and other organization practicing TQM or other quality program.

**Table 1. Factors and sub factors affecting cutting forces**

| S. no. | Factors | Sub-factors | References |
|---|---|---|---|
| 1. | Work material | Temperature, hardness, Tensile strength | joseph (1995) |
| 2. | Cutter runout | Uncut chip thickness, shear angle, Friction angle | Min Wan et al.(2014) |
| 3. | Tool Geometry | Tool extension length, rack angle, Deflection of cutting tool | Renjith V B et al.(2013) |
| 4. | Penetration strategies | Straight penetration(sp), half revolution Penetration(hrp), quarter revolution penetration(qrp) | Vishal S.Sharma et al.(2014) |
| 5. | Machine tool | Cutting speed, feed rate, depth of cut, Tool overhang length | Mr.Vinay Babu Gada, et al.(2013) |

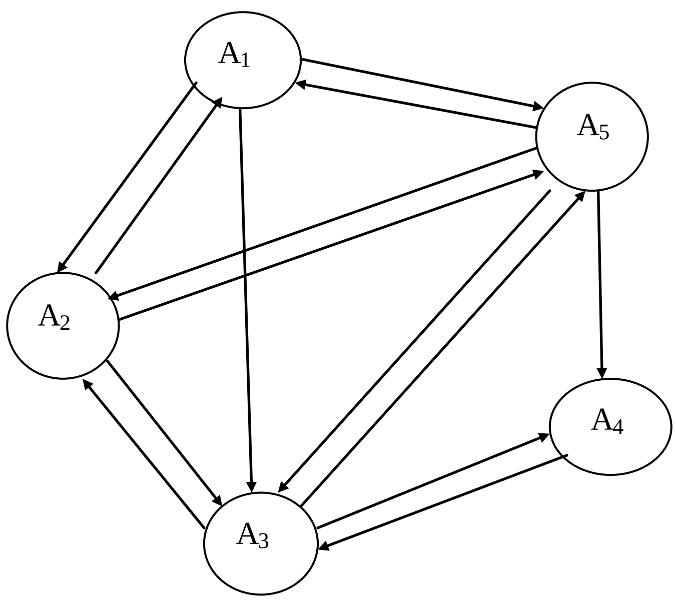


**Fig. 1** Digraph representing interdependence among factors 1 work material 2 cutter runout, 3 tool geometry, 4 penetration strategies, 5 machine tool

 

$$
\text{VPM} = B = \begin{array}{c} \begin{array}{ccccc} A1 & A2 & A3 & A4 & A5 \end{array} \\ \begin{pmatrix} A_1 & a_{12} & a_{13} & a_{14} & a_{15} \\ a_{21} & A_2 & a_{23} & a_{24} & a_2 \\ 0 & a_{32} & A_3 & a_{34} & a_{35} \\ 0 & a_{42} & a_{43} & A_4 & 0 \\ A_{51} & a_{52} & a_{53} & a_{54} & A_5 \end{pmatrix} \end{array} \begin{array}{c} \\ A1 \\ A2 \\ A3 \\ A4 \\ A5 \end{array} \qquad (1)
$$

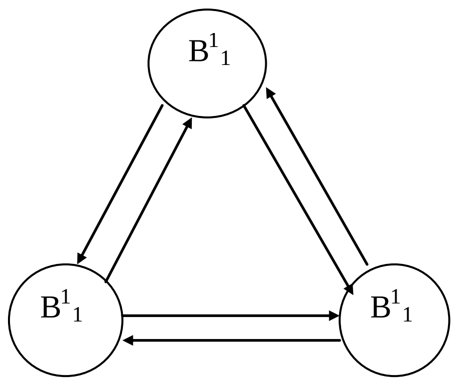


**Fig. 2** Digraph representing sub-factors affecting work-piece: 1 temp. 2 hardness 3 tensile strength

**Table 2.** Quantification of factors affecting cutting forces

| Qualitative measure of factors | Assigned value/inheritance |
|---|---|
| Exceptionally low | 1 |
| Very low | 2 |
| Low | 3 |
| Below average | 4 |
| Average | 5 |
| Above average | 6 |
| High | 7 |
| Very high | 8 |
| Exceptionally high | 9 |

 

**Table 3.** Quantification of interdependence/off diagonal elements

| S. no. | Qualitative Measure | $a_{ij}$ |
|---|---|---|
| 1 | Very strong | 5 |
| 2 | Strong | 4 |
| 3 | Medium | 3 |
| 4 | Weak | 2 |
| 5 | Very weak | 1 |

**Table 4.** Results of air hardened die steel(H-11)

| S. no. | Temp.($^0$C) | Hardness(HRC) | Tensile strength (Mpa) |
|---|---|---|---|
| 1 | 510 | 56.5 | 2,120 |
| 2 | 540 | 56.0 | 2,005 |
| 3 | 565 | 52.0 | 1,855 |
| 4 | 595 | 45.0 | 1,540 |
| 5 | 650 | 33.0 | 1,060 |

**Results are taken from joseph (1995)**

**Quantification**

Each factor affecting the cutting force is identified as a subsystem and GTA is applied in each subsystem. Subsystem affecting cutting force is evaluated for permanent function considering various subfactors affecting the subsystem. The dependencies of subfactors at subsystem level are visualized through digraphs. These digraphs lead to the inheritance of main factors at system level through matrix and measures. The corresponding variable permanent matrices are then derived for each subsystem and permanent function of each VPM is evaluated. The permanent functions of these matrices will evaluate the cutting force. Thus, GTA may be applied at every level (Jangra et al. 2002).
For this, inheritance of factors related to diagonal elements and interdependence of non-diagonal elements have to be developed as in Tables 2 and 3. However, values can be assigned through proper interpretation by the experts in the field. Table 3 suggests these qualitative values of interdependencies of elements (Table 4). From the above discussion of graph theory, it can be deduced that this theory rests upon the inter-dependencies among the factors and sub-factors, so these must be precisely defined. Graph theory literature illustrates that there is only a limited work on application of this theory on machinability aspects related to industries. So,the objectives of the work covered in the paper is to:-

- Apply graph theory to practical work.
- Develop a methodology to inter-relate this practical work with graph theory.
- Making complete use of graph theory to study the interdependencies among factors, that are not defined by any theory.

**3.5 Index value for work material (A1)**

Sub factors affecting work material and their interactions have been illustrated with the help of digraph as in Fig.2

**Table 5.** Inheritance of sub-factors for work material (diagonal elements)

| S. no. | Temperature($B^1_1$) | Hardness ($B^1_2$) | Tensile strength ($B^1_3$) |
|---|---|---|---|
| 1 | 6 | 5 | 7 |
| 2 | 7 | 6 | 7 |
| 3 | 9 | 7 | 6 |
| 4 | 5 | 7 | 4 |
| 5 | 4 | 7 | 4 |

**Table 6.** Index Value for work piece for different combination

| Subsystem with different sub factor combination | $(A_1)_1$ | $(A_1)_2$ | $(A_1)_3$ | $(A_1)_4$ | $(A_1)_5$ |
|---|---|---|---|---|---|
| Index value | 483 | 585 | 680 | 380 | 344 |

The superscript represents the factor and the subscript represents the sub factors affecting factor (work-piece). Experimental data proposed by Joseph (Joseph and Tool Materials 1995) has been used to evaluate the inheritance of diagonal elements. The results show the significant effect that temperature has on hardness and tensile strength of die steels.

At higher temperatures, the die steels start losing their hardness and tensile strength. The inheritance of sub-factors has been assigned value in range of 1–9 as shown in Table 5 with the help of Table 2.

The VPM for each sub-system based on digraph showing their inter-relationship have been developed and based on detailed literature review, the numeric values of interdependences between sub-factors (non-diagonal elements) have been taken from Table 3.
Value of permanent function for work material (A1) can be calculated using Eq.3.

$$\mathrm{VPM} = A_1 = \begin{array}{c c} \begin{array}{ccc} 1 & 2 & 3 \end{array} & \\ \begin{pmatrix} B^1_1 & 3 & 2 \\ 5 & B^1_2 & 2 \\ 5 & 4 & B^1_3 \end{pmatrix} & \begin{array}{c} 1 \\ 2 \\ 3 \end{array} \end{array} \qquad (3)$$

Higher values of index reflect the best conditions of cutting force, because at $565^0$ the die steel maintains optimum hardness and tensile strength (Table 6).

**3.6 Index value for Cutter runout (A2)**

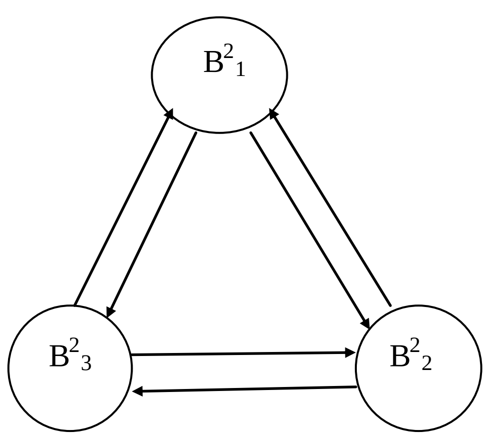

**Fig.3.** Digraph representing sub-factors affecting cutter runout: 1 uncut chip thickness, 2 shear angle 3 friction angle

Min Wan et al.(2014) was stated that the accurate determination of cutting force coefficients is essential for reliable prediction of cutting force in milling process. A unified and simple method is proposed to develop unified instantaneous cutting force model for flat end mills with variable geometries. By transforming the cutting forces measured in Cartesian coordinate system into a local system on normal plane, novel procedures and algorithms are presented to establish the instantaneous models of shear stress, shear angle and normal friction angle involved in the cutting force coefficients. The advantage of the new method lies in that the models developed from a few tests.

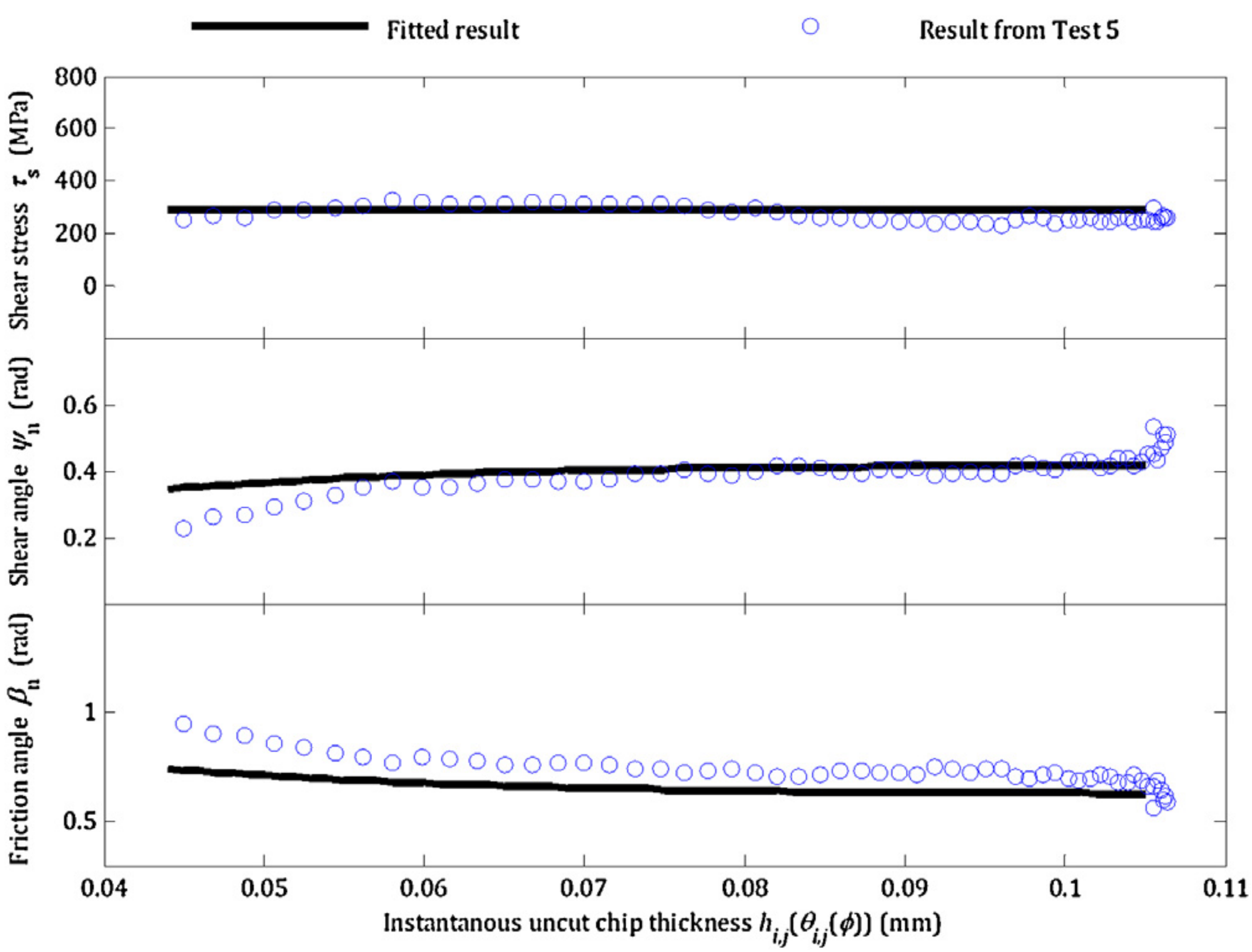


**Fig.3.1** Comparison of uncut chip thickness Vs $\beta_n$ , $\tau_s$ $\psi_n$

| Sr. no. | Uncut chip Thickness | friction angle | shear angle |
|---|---|---|---|
| 1 | 0.05 | 0.5 | 0.2 |
| 2 | 0.06 | 0.6 | 0.4 |
| 3 | 0.07 | 1.0 | 0.6 |

 

**Table 7.** Experimental result for uncut chip thickness in milling

**Results have been taken from Min wan et al. (2014)**

Sub factors related to cutter runout and their interactions have been illustrated with the help of digraph as in Fig. 3. The superscript represents the factor and the subscript represents the sub factor affecting factor (cutter runout). Based on the need, inheritance values have been assigned to sub-factors affecting cutter runout (Table 8). The VPM for each sub-system based on digraph showing their inter-relationship have been developed and based on detailed literature review, the numeric values of interdependences between sub-factors (non-diagonal elements) have been taken from Table 3.

Value of permanent function for cutter runout (A2) can be calculated using Eq. 4.

$$\text{VPM} = A_2 = \begin{array}{c c} \begin{array}{ccc} 1 & 2 & 3 \end{array} & \\ \begin{pmatrix} B^2{}_1 & 3 & 2 \\ 5 & B^2{}_2 & 4 \\ 3 & 4 & B^2{}_3 \end{pmatrix} & \begin{array}{c} 1 \\ 2 \\ 3 \end{array} \end{array} \qquad (4)$$

**Table 8.** Inheritance of sub-factors in cutter runout (diagonal elements)

| Uncut chip thickness | inheritance ($B^2{}_1$) | friction angle | inheritance ($B^2{}_2$) | shear angle | inheritance ($B^2{}_3$) |
|---|---|---|---|---|---|
| 0.05 | 4 | 0.5 | 5 | 0.2 | 6 |
| 0.06 | 7 | 0.6 | 6 | 0.4 | 8 |
| 0.07 | 7 | 1.0 | 6 | 0.6 | 6 |

**Table 9.** Index value for cutter run out

| Subsystem with different Sub factor combination | $(A_2)_1$ | $(A_2)_2$ | $(A_2)_3$ |
|---|---|---|---|
| Index value | 380 | 680 | 566 |

It is found that shear angle increases along with the increase of instantaneous uncut chip thickness, whereas normal friction angle decreases.

Higher index value $(A_2)_2$, illustrates that friction angle have been preferred in case of cutter runout on CNC Milling (Table 9).

### 3.7 Index value for tool geometry ($A_3$)

Sub factors affecting tool geometry and their interactions have been illustrated with the help of digraph as in Fig. 4
The superscript represents the factor and the subscript represents the sub factor affecting factor (tool geometry). Tool geometry is a function of tool extension length, rake angle and deflection of cutting tool. Based on the application,

 

inheritance values have been assigned to sub-factors affecting tool geometry. Value of permanent function for tool geometry (A3) can be calculated using Eq.5.

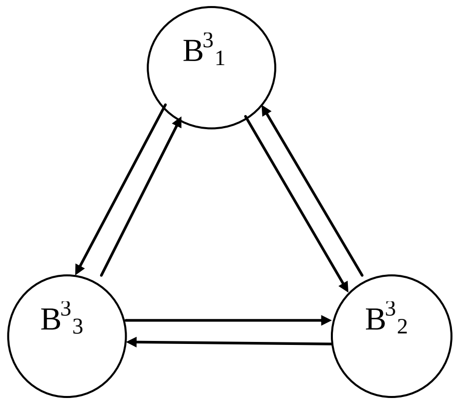


**Fig. 4.** Digraph representing sub-factors affecting tool geometry: 1. tool extension length 2. rack angle 3. Deflection of cutting tool

$$\text{VPM} = A_3 = \begin{array}{cc} \begin{array}{ccc} 1 & 2 & 3 \end{array} & \\ \begin{pmatrix} B^3{}_1 & 3 & 4 \\ 5 & B^3{}_2 & 3 \\ 4 & 3 & B^3{}_3 \end{pmatrix} & \begin{array}{c} 1 \\ 2 \\ 3 \end{array} \end{array} \qquad (5)$$

**Table 10.** Experimental results for tool geometry

| S. no. | Rake angle (degree) | Tool extension length (mm) | Deflection (mm) |
|---|---|---|---|
| 1 | 10 | 30 | 0.04791 |
| 2 | 15 | 35 | 0.06248 |
| 3 | 0 | 25 | 0.0123 |

**Results have been taken from Renjith V B et al. (2013)**

**Table 11.** Inheritance of sub factors in tool geometry (diagonal elements)

| Rack Angle | Inheritance ($B^3{}_1$) | Tool extension length | Inheritance ($B^3{}_2$) | Deflection | Inheritance ($B^3{}_3$) |
|---|---|---|---|---|---|
| 10 | 4 | 30 | 5 | 0.04791 | 5 |
| 15 | 5 | 35 | 6 | 0.06248 | 6 |
| 0 | 7 | 25 | 6 | 0.0123 | 8 |

**Table 12.** Index Value for tool geometry

| Subsystem with different Sub factor combination | $(A_3)_1$ | $(A_3)_2$ | $(A_3)_3$ |
|---|---|---|---|
| Index value | 387 | 507 | 711 |

Putting the value of diagonal elements, index under different combinations can be calculated.
Higher value of (MI) indicates that cutter having rake angle of 0 and tool extension length of 25 is usually preferred which give minimum deflection i.e. 0.0123 mm.

### 3.8 Index value for penetration strategies ($A_4$)

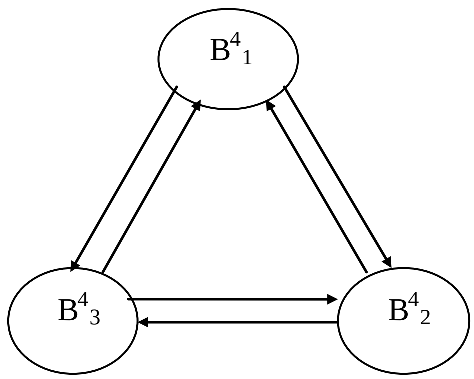


**Fig. 5.** Digraph representing sub-factors affecting penetration strategies: 1. straight penetration 2. half revolution penetration 3. quarter revolution penetration

The penetration strategies (PS), used in the study, are straight penetration (SP), half revolution penetration (HRP), and quarter revolution penetration (QRP). In SP, the mill engages with the part following a straight line trajectory; there is no Z-axis displacement during this movement. For HRP, the tool follows a half helical path to engage with the part; during this movement, it also travels equal to P/4 in Z-axis. QRP utilizes quarter helical trajectory for engagement with the part and movement in Z-axis. HRP and QRP strategies are employed in industry; the SP strategy is considered for comparisons with them.

the process can be used to machine difficult-to-machine materials such as titanium alloys, tool steels, stainless steels, hardened steels, and other super alloys. The machine used for the experiments was a three-axis vertical machining center (Deckel Maho DMC 65V). Aluminum alloy (AlCu4Mg) was opted for study as it exhibits good machinability characteristics. Solid carbide TiCN-coated thread mills were used for the study. Cutting forces were measured with 9123 Kistler rotating dynamometer and data was processed using DASY Lab acquisition software.

 

**Table 13.** Experimental data for full machining and penetration

| Sr. no. | D (mm) | Mill | Ps | $N_{wt}$ (N) | $RF_{ptp}$ (N) | $RF_{rms}$ | $RF_{rms}/N_{wt}$ (N) |
|---|---|---|---|---|---|---|---|
| 1 | 20 | T1 | FM | 1.02 | 423 | 196 | 192 |
| 2 | 20 | T1 | SP | 1.68[a] | 653 | 322 | 192 |
| 3 | 20 | T1 | HRP | 1.02[a] | 490 | 213 | 209 |
| 4 | 20 | T1 | QRP | 1.02[a] | 451 | 207 | 203 |
| 5 | 20 | T2 | FM | 1.67 | 193 | 189 | 113 |
| 6 | 20 | T2 | SP | 2.46[a] | 604 | 350 | 142 |
| 7 | 20 | T2 | HRP | 1.67[a] | 361 | 213 | 128 |
| 8 | 20 | T2 | QRP | 1.67[a] | 354 | 204 | 12 |

**Results have been taken from Vishal S. Sharma et al. (2014)**

**Table 14** Inheritance of sub factors in penetration strategies (diagonal elements)

| SP ($B^4{}_1$) | HRP ($B^4{}_2$) | QRP ($B^4{}_3$) |
|---|---|---|
| 5 | 7 | 9 |

Vishal S. Sharma et al (2014). Various types of Penetration strategies have been illustrated with the help of digraph as in Fig. 5. Here the superscript represents the factor and the subscript represents the sub factor affecting factor (Penetration strategies) (Tables 10, 11, 12,13, 14).

Value of permanent function for Penetration strategies (A4) can be calculated using Eq. 6.

$$VPM = A_4 = \begin{array}{c} \begin{array}{ccc} 1 & 2 & 3 \end{array} \\ \begin{pmatrix} B^4{}_1 & 1 & 2 \\ 2 & B^4{}_2 & 1 \\ 2 & 2 & B^4{}_3 \end{pmatrix} \end{array} \begin{array}{c} \\ 1 \\ 2 \\ 3 \end{array} \qquad (6)$$

Index value for Eq. (6) is 380.

1.Straight penetration leads to more resultant cutting forces as compared to half revolution penetration and quarter revolution penetration strategies for all the three milling cutters because flute working angle ($\theta_{twa}$) becomes double at the end of penetration strategy.
2.The cutting forces are minimum for quarter revolution penetration because of progressive increase of radial penetration ($r_p$) and the number of working teeth ($N_{wt}$).
3.The peak to peak variations of the resultant cutting force is linked to the number or working teeth, and according to this criterion T2 mill appears to be the best among the studied tools.

 

**3.9 Index value for Machine tool ($A_5$)**

Sub- factors affecting machine tool and their interrelationship have been demonstrated with the help of digraph as in Fig. 6.

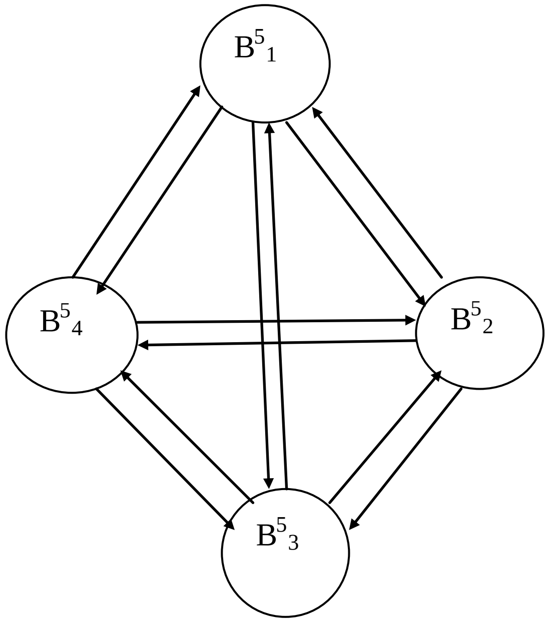


**Fig. 6** Digraph representing sub-factors of machine tool: 1 cutting speed 2 feed rate 3 depth of cut 4 tool overhang length

Many engineering components manufactured using casting, forming and other processes often require machining as their end operation. Machining or metal cutting is an important manufacturing process. With the modern trend of machine tool development, accuracy and reliability are becoming prominent features. To achieve higher accuracy and productivity, it requires consideration of dynamic instability of cutting process. When there is a relative motion present between the tool and work piece, the performance of the operations may not be satisfactory. The machine tool vibrations have detrimental effect on tool life which in turn lowers the productivity and increases cost of production.

**Fig.7 Five-axis machining center with rotating table and computer interface**

**Table 15.** Operating parameters and their levels used in the experiments:

 

| Work piece material | Cutting speed in(rpm) | Feed rate(mm/rev) | Depth of cut(mm) | Tool overhang length(mm) |
|---|---|---|---|---|
| EN 24 Steel | 7, 14, 22 | 0.1(constant) | 0.1, 0.2, 0.3, 0.4<br>0.5, 0.6, 0.7 | 54,57,59,61 |
| EN 8 Steel | 7, 14, 22 | 0.1(constant) | 0.1, 0.2, 0.3, 0.4<br>0.5, 0.6, 0.7 | 53, 57, 60,63 |
| Mild Steel | 7, 14, 22 | 0.1, 0.138, 0.175<br>0.2, 0.275, 0.35, 0.5 | 0.1(constant) | 54,57,59,61 |
| Aluminum | 7, 14, 22 | 0.1, 0.138, 0.175<br>0.2, 0.275, 0.35, 0.5 | 0.1(constant) | 53,54,58,62 |

**Results have been taken from Vinay Babu Gada et al. (2013)**

The cutting operation is limited to a short range since the structural stiffness rapidly increases as the tool advances inwards. The cutting speed (v),feed rate (f),depth of cut (d) and tool overhang length(*l*) are progressively changed to obtain the cutting forces (Feed force(Fx), Radial force(Fy) and Tangential force(Fz) as well as critical chatter lengths (*l*c).The tool overhang refers to the distance from the tool holder to the end of cutting edge. In the present case the tool overhang lengths are varied between 53 to 63 mm.

Overhang lengths of the tool is measured using a milli-meter scale. An attached tool post strain gauge dynamometer platform is employed to measure the amplitudes of the three cutting forces. Here tool dynometer with strain gauge support (PE1-845122) is mounted on the lathe itself and this strain gauge capacity ranges from 0.1 mV to 3V. Here force values are obtained in terms of voltage and the force in Newton is obtained by the available multiplication factors.

At low speed, cutting forces increases gradually with overhanging lengths and at high speeds initially forces increase slowly at low overhanging lengths and at high overhanging length forces increase very rapidly. The static forces generally increase with the subsequent increase in feed rate. This has been attributed to the fact that the area of cut subsequently increased per cycle of cut, hence more shearing had to be done which required more force. Increasing the DOC generally resulted in a proportional increase in the static cutting forces. The fresh (sharp) tool static cutting forces increased linearly when overhanging length increases, forces increase both in X, Y and Z Direction at low overhanging length forces increases slowly and at high over hanging length increases very rapidly. Above all parameters effects on critical chatter lengths i.e. by increasing above all parameters chatter lengths decreases.

Based on the optimum values of process parameters taken from Table 15, the inheritance values have been assigned to sub-factors of machine tool as in Table 16. Value of permanent function for machine tool (A5) can be calculated using Eq. 7

**Table 16.** Inheritance of sub factors of machine tool (diagonal elements)

| Cutting speed | ($B^5_1$) | Feed rate | ($B^5_2$) | Depth of cut | ($B^5_3$) | Tool overhang length | ($B^5_4$) |
|---|---|---|---|---|---|---|---|
| 7 | 6 | 0.1 | 6 | 0.1 | 5 | 53 | 4 |
| 14 | 7 | 0.2 | 8 | 0.2 | 6 | 57 | 5 |
| 18 | 6 | 0.3 | 5 | 0.4 | 4 | 59 | 4 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 22 | 5 | 0.5 | 6 | 0.6 | 4 | 63 | 3 |

**Table 17.** Index value for machine tool

| Subsystem with different sub factor Combination | $(A_5)_1$ | $(A_5)_2$ | $(A_5)_3$ | $(A_5)_4$ |
|---|---|---|---|---|
| Index value | 3,496 | 5,328 | 2,968 | 2,616 |

$$\mathrm{VPM} = A_5 = \begin{array}{c} \begin{array}{ccc} 1 & 2 & 3 \end{array} \\ \begin{pmatrix} B^5{}_1 & 3 & 2 \\ 4 & B^5{}_2 & 3 \\ 3 & 3 & B^5{}_3 \end{pmatrix} \end{array} \begin{array}{c} \\ 1 \\ 2 \\ 3 \end{array} \qquad (7)$$

Index value indicates that feed rate is the most significant sub factor affecting cutting force, followed by cutting speed ,depth of cut and tool overhang length. (Tables 16, 17).

**Table 18** Index Value for under different sub-factor combination

| S. no. | Subsystem combination | Index value |
|---|---|---|
| 1 | $(A_1)_1(A_2)_1(A_3)_1(A_4)_1(A_5)_1$ | $9.43 \times 10^{13}$ |
| 2 | $(A_1)_2(A_2)_2(A_3)_2(A_4)_2(A_5)_2$ | $4.08 \times 10^{14}$ |
| 3 | $(A_1)_3(A_2)_3(A_3)_3(A_4)_3(A_5)_3$ | $3.09 \times 10^{14}$ |
| 4 | $(A_1)_4 (A_2)_4(A_3)_4(A_4)_4(A_5)_4$ | $1.52 \times 10^{14}$ |
| 5 | $(A_1)_5(A_2)_5(A_3)_5(A_4)_5(A_5)_5$ | $2.40 \times 10^{14}$ |

$$\mathrm{VPM} = B^* = \begin{array}{c} \begin{array}{ccccc} A1 & A2 & A3 & A4 & A5 \end{array} \\ \begin{pmatrix} A1 & 3 & 2 & 2 & 5 \\ 4 & A2 & 4 & 2 & 3 \\ 0 & 3 & A3 & 4 & 4 \\ 0 & 2 & 4 & A4 & 0 \\ 2 & 1 & 2 & 3 & A5 \end{pmatrix} \end{array} \begin{array}{c} \\ A1 \\ A2 \\ A3 \\ A4 \\ A5 \end{array} \qquad (8)$$

Now, the need is to calculate the MI of the complete system. The VPM is used and the value of diagonal elements has been determined by the results obtained for each sub factor. MI has been calculated under different subsystem combinations. Value of permanent function for Cutting force (A) can be calculated using Eq. 8.
Higher index value of sub-system corresponds to substantial influence on the cutting force. Machine tool subsystem has the highest index value, so it is the most important factor corresponding to cutting force. Higher index value of subsystem combination demonstrates that feed rate is the most crucial machining parameter influencing cutting force, followed by cutting speed and depth of cut

## 4. RESULTS AND DISCUSSION:-

Index value is helpful in evaluating the important parameters affecting Cutting Force at both system and sub-system level. Graph theory technique can be used to evaluate the weak and the strong factors and sub-factors. In present work, work-piece, cutter runout, tool geometry, penetration strategies and machine tool have been taken as factors affecting Cutting force. Firstly, the tensile strength, temperature and hardness of wok piece have been worked out and the inter-relationship have been developed at sub-system level and based on index values, the optimum values of tensile strength, hardness and temperature have been taken for work piece to carry out experimentation. Similarly, impact of friction angle, shear angle and uncut chip thickness on cutter runout have been evaluated and based on index values of $(A_2)_2$ and $(A_3)_3$, it has been found that shear angle increases along with the increase of instantaneous uncut chip thickness, whereas normal friction angle decreases.

Higher index value $(A_2)_2$, illustrates that friction angle have been preferred in case of cutter runout on CNC Milling to achieve good surface finish values. experimentation has been conducted by Mr.Vinay Babu Gada et al (2013) are used to determine the range of machining parameters like feed rate, depth of cut, cutting speed and tool overhang length. Results reveal that machine tool is the most important factor at the system level and machine tool index value illustrates that feed rate is the most vital parameter affecting cutting force, followed by cutting speed, tool overhang length and depth of cut at the sub-system level. At last, Index value is calculated for complete system. Combination 2 reveals the best results in terms of cutting force and hence is the most preferred combination of sub-factors to achie optimum cutting force.

## 5.CONCLUSIONS:-

To determine cutting forces, graph theory proves to be a capable system that can compare the parameters at both system and subsystem level and helps in quantifying the influence of various factors and sub-factors. By using this technique, the evaluation of the weak and the strong factors and sub factors is done. Graph theory provides flexibility in terms of number of factors, sub-factors and help in predicting the most influencing interactions between sub-factors. By using this, machinability can also be evaluated in terms of quality characteristics like material removal rate, surface roughness, dimensional accuracy etc. In nutshell, it is concluded that cutting force index can be a very effective tool for achieving optimum solutions to production problems.

## 6. SCOPE FOR FUTURE WORK

1. Using this methodology, machinability of any material can be evaluated and compared under the influence of any number of factors and subfactors.
2. Similar to this methodology, machinability can be evaluated in terms of other machining performances such as surface finish, dimensional precision, tool life, etc.

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