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

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

Ph.D. Thesis

by

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PREFACE

The eight chapter and appendices of this Thesis follow what the author feels is a logical progression from Computer Aided Process Planning through its implementations in Computer Aided Manufacturing CIM-environment.

Chapter one introduces Computer Integrated Manufacturing (CIM) to the reader.

The heart of operating manufacturing system automated or not is the Production Planning and Control function; it is the topic of *Chapter two*.

Chapter three presents Computer Aided Process Planning (CAPP). From the Thesis point of view this chapter is of very importance as it covers the most important aim of the Thesis. The role of Computer Aided Process Planning (CAPP) is very important as it links Computer Aided Design (CAD) to Computer Aided Manufacturing (CAM). A key to effective CAPP is Group Technology (GT), which was not the aim of this Thesis to be discussed so broadly as it is.

Chapter four covers the fundamentals of optimizations and general principles in hierarchical levels like "top-down" optimization.

Tool life synchronization in *Chapter five* covers the first step in optimization problems in this Thesis.

Chapter six of the Thesis presents the Determination of the optimum rate of stock removal factor in machining processes.

Chapter seven as the most important part of the Thesis is searching for a solution for optimization of the total cost of the operation.

Chapter eight covers the scientific results of the Thesis.

The rest of the submitted Thesis covers the appendices, publications along with the important references used for fulfillment of this Dissertation.

It is impossible to thank all those who helped me to prepare this Thesis.

First of all, thanks have to go to *Prof Tóth, Tibor* my scientific advisor and teacher for his many helpful comments and suggestion and contribution with specific thought in this Thesis. Furthermore during my undergraduate period of studying *Prof Tóth, Tibor* gave me lectures in two important subjects namely “Fundamentals of Production Engineering”, and “Technology Planning for Discrete Manufacturing”. These two subjects provided me with knowledge and information in technology and production systems. I had also lectures with *Prof Tóth, Tibor* during my doctoral period of studying and his patience and sympathies are not forgetful. In the end I have to declare that I owe a lot to *Prof Tóth, Tibor* in connection with fulfillment of this Dissertation. I will never forget his words that he always said, *We Trust in God* .

I would like to express my special appreciation to *Dr Nagy, Ferenc* the mathematician for his help in developing the programs. His gentle activities and thought in connection with my Dissertation were very important.

The author would like to express his thanks to *Dr Erdélyi Ferenc* for his previous help in connection with CIM system during the author’s doctoral period of studying.

I would like to thank *Dr Rayegani, Farzad* my friend for his contribution and discussion in writing and presenting the joint papers in several conferences.

Finally I have to thank my wife *Zsuzsa Dadvandipour* and my family in Iran especially to my mother *Aghdas Boukani-Neghad*, my very kind sister *Shahnaz Biuk* and my very dear brother *Ahad Dadvandipour* and other relatives and friends of mine for their encouragement in connection with my Ph.D. as without support and understanding of them this Thesis could not have been written.

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Introduction

Computer Integrated Manufacturing (CIM) provides a complete automation of manufacturing companies, with all processes working under computer control systems linking them together. It includes Computer Aided Design (CAD), Computer Aided Manufacturing (CAM), Computer Aided Process Planning (CAPP), Computer Numerical Control of machine tools (CNC), Direct (Distributed) Numerical Control of machine tools (DNC), Flexible Manufacturing Systems (FMSs), Automated Storage and Retrieval Systems (ASRS), Automated Guided Vehicles (AGVs), the use of robotics and automated conveyance, Computerized Scheduling and Production Control and a business system integrated by a common database. CAD/CAM is very essential to reducing cycle times in an organization. Computer Aided Process Planning (CAPP) emerges as a key factor in CAD/CAM integration because it is the link between CAD and CAM. CAD techniques make use of Group Technology (GT) to create similar geometries for quick retrieval electronic files replacing drawing rooms. CAD/CAM integrated system provides design and drafting, planning and scheduling, and fabrication capabilities. CAD provides the electronic part images, and CAM provides the facility for tool path cutters to take on the workpiece. Advanced software programs can analyse and test designs before a prototype is made. Finite element analysis programs allow engineers to predict stress points on a part, and the effects of loading. Generative, variant and vario-generative process planning [4,20] are advanced CAPP methods in integration of CAD/CAM.

This Thesis is about solving some *optimization problems of Computer Aided Process Planning (CAPP) in CIM environment concerning machining processes*. In this respect optimum determination of cutting parameters (depth of cut, feed rate and cutting speed) is of a great importance especially for NC/CNC machine tools. Increasing the intensity of these parameters may result in decreasing the machining time of the given operation, but at the same time, it increases the tool cost as a consequence of loading and wearing of the tool, which is not economical and cost effective. Then we can realise the fact that there will be contrasted effects if we do not select appropriate cutting parameters. In order to find a reasonable compromise it is necessary to solve optimization problems. This part of the Thesis aims at *optimization of tool life* using appropriate cutting parameters. This trial results in decreasing of the feed rate and the spindle speed along with arranging the surfaces of the workpiece to be machined in accordance with decreasing machining times. It is resulting in increasing of the tool life. Solution of this optimization problem needs determination of machining time, spindle speed, determination of weighted average tool life taking into consideration the local tool lives for number of cuts and database using computer program. *Determination of the optimum rate of stock removal factor* is another optimization problem related to this Thesis. Determination of optimum stock removal factor in machining processes is very important, because the intensive parameter values (depth of cut, feed rate and cutting speed) are originating from its rate. The resultant output (the optimum rate of stock removal factor) comes from a new idea: suggests that *the total cost of the operation* for the machining processes to be an *objective function* and *the limit of total machining time* proposed by the dispatcher to be *the constraint* for the solution of this optimization problem. Using the total cost of operation as an objective function and the limit of total machining time give the chance to the up-to date companies that try to increase their productivity, to face rapidly changing market conditions, to improve product design, and to increase product quality for better customer satisfaction in time. To solve the problem a mathematical model based on *Lagrange multiplier* method has been applied. The derivation of the mathematical model results in *a new optimum rate of stock removal factor*, which its rate is the same for all the layers in question. For example in case of turning processes it is clear that the smaller the turning diameter the greater the cutting speed but as the rate of the stock removal factor for the solution of this optimization problem is the same for the all the layers, then in this case the depth cut and feed rate should be decreased. This is an advanced solution for optimization of cutting processes. *Optimization of the total cost of the operation* is very fundamental and significant problem in machining processes. This covers another important part of this Thesis. The new idea works based on the variable rate of stock removal factors. The outputs realising these factors employs *the total cost of the operation* as an *objective function* and *the maximum weighted average tool life allowed to be utilized* as *the constraint*. To solve this problem a mathematical model also based on *Lagrange multiplier* method has been developed. The derivation of the mathematical model results in *highly non-linear system of equations*, which we have to solve for rate of stock removal factors and the range of Lagrange multiplier. Converting the highly non-linear system of equations needs application of a special matrix so called Hasse matrix. Using Hasse matrix a linear system of equations can obtain for the solution of the rate of stock removal factors for each chain and Lagrange multiplier as well (constant). Substituting the obtained results in the objective function is the solution of this optimisation problem. A computer program and numerical method have been used for solution of these optimization problems. The above-mentioned cases are the new results in optimization problems for turning processes and have been described in details in *chapters 5*, *6* and *7* of this Thesis. The results may also be generalized for other cutting processes like as milling, drilling and grinding so on as well.

1.1. Concept of Computer Integrated Manufacturing CIM

Computer-Integrated Manufacturing (CIM) [5] as a strategy helps to improve the performance of a manufacturing firm by integrating various functional areas of manufacturing. Realising the importance of CIM both from the investment and operational efficiency points of view, it is well known that companies need to increase their productivity, to face rapidly changing market conditions, to improve product design, and to increase product quality for better customer satisfaction. CIM can be defined as the rational use of Information Technology (IT) to support production management (including product design and engineering, process planning, numerical control programming, production planning and control, and quality control) and factory automation to favour communication, co-operation, and co-ordination of the many heterogeneous functions and components of manufacturing enterprise to increase organisation and personnel productivity and efficiency. Many of the new methodologies have been already introduced to improve performance of CIM such as Just-in-time (JIT) manufacturing [10], Total Quality Management (TQM), Design For Manufacturing (DFM), and World Class Manufacturing (WCM) etc. Unfortunately there is no full agreement to define CIM. To some, CIM is a program, because it offers a number of useful and potential opportunities for improving the system performance of a manufacturing company or an enterprise while to others, the overall objective of CIM is to integrate different software applications, functional areas, tasks, and areas of automation into a coherent whole to achieve the business objectives of the company, but generally thinking, it seems likely that eventually most manufacturing firms will implement CIM to some extent. This is due to: The rapidly declining costs of computer and communications hardware, and increasing pressure to improve productivity and reduce labour costs. These will be accompanied by flexible computerization of control, communication, and management functions. Complete implementation of CIM results in the linking of islands of automation restricted to the individual components of the job shop (FMSs, CAD/CAM, CNC) and the information flow in a business organisation from entry of an order through every step of the value chain to shipment of the finished goods.

1.1.1. Historical background

In the late sixties, the concept of complete automation of manufacturing processes was emerged and most of the manufacturers dreamt of having full automatic factories in the future. However, nowadays it does not seem a full popular agreement over this idea as strong as it was. Such change of attitude is due to the change in the rules of the market. During the early seventies the objective of nothing but *only productivity* gave way to other more objectives like *flexibility* and *quality*. The result of the change was competition among the companies in their policy of trading inventories. The new situation resulted in developing of different industrial organisation, which aimed to increase the flexibility of a company and to decrease the administrative procedures in its management and control system. The idea of having flexible and qualified manufacturing system was based on giving many responsibilities to the personnel involved directly in production activities. But after some time it was revealed that over-automation had unwelcome consequences. As an example, the functions, which could be performed by manual and simple mechanical devices, had been replaced by rather very complex computer technology. It means that the idea of simplicity had been lost and replaced by complexity in production activities of the manufactures. Computerisation had become a universal and there was no attempt to find a less complex alternative. Meantime the new approach had caused the workers to re-evaluate their jobs and improve the performance of the given tasks. In spite of the fact there were opponents of complete automation, but they were not very important effects on the idea of those who desired of having a total integration of production by computerisation, because it was unreasonable to rely only on human effort and to rule out the information exchange through the computer. *Merchant, E.* [30] proposed CIM concept at the end of seventies in the United States of America. Considering the most characteristic events with approximate dates published in professional literature, this phase of the CIM had preliminary branches, which were as follows:

- The first branch was drafting which was started at the early fifties and developed until 1965 and included scientific analysis, computer drafting and geometric modelling.

- The second branch is Process Planning and Production Planning & Scheduling, which was started in 1951 and developed until 1958 and included Group Technology (GT), coding and Computer Aided Process Planning (CAPP).

- The third branch was the supporting to the manufacturing system which was started in 1952 and developed until 1969 included Numerical Control (NC) in 1952, Computerised Numerical Control (CNC) in1957, Direct (Distributed) Numerical Control of machine tools (DNC) in 1961, Adaptive Control (AC) in 1965, and Computer Aided Manufacturing (CAM) in 1969.

In reality these three branches led to CAD/CAM integration in 1973.

- The fourth branch was the utilisation of Artificial Intelligence (AI), which was started in 1963 and in its first stage developed until 1975 and it included Knowledge Based Visualisation (KBV) in 1963, Expert System in 1966, Robot Sensation in 1967 and Expert System Shell in 1975.

In 1973, *Harrington, J.* [17] published the initial concepts of CIM in a book entitled "Computer Integrated Manufacturing". Initially these concepts received little attention. It was not until about 1984 that people began to realize the potential benefits these concepts promised. Since 1984, thousands of articles have been written on this subject. In his Thesis *Erdélyi, F.* [14] presents the "Computerized Control of Machine Tools and Discrete Manufacturing Processes" and proposes four phases in CIM as follows: The basic CIM was born in early seventies and was named CIM-I. It included Manufacturing Automation, NC technique, Integrated Material and Data Processing. The second phase of integration was developed at the end of seventies so called CIM-II, which included Computer Aided Engineering Design and Manufacturing, (CAD/CAM), Local Area Network (LAN), and Manufacturing Automation Protocol (MAP). The third phase of CIM was CIM-III, which was in the early eighties and included Integrated Infrastructure based on Information Technology, Manufacturing Information System (MIS), Computer Aided Engineering (CAE), Computer Aided Manufacturing (CAM), and Open System Structure (OPS). The latest kind of CIM is CIM-IV and it started at the early nineties and includes Computer Integrated Enterprise (CIE), Intelligent Manufacturing [6,37,36]. In the early eighties the idea of integrating the various functions of the companies (design and methods, production, administration, accounting, marketing etc.) using common data storage was emerged, but because of incompatibilities among individual items of hardware the idea faced the problem of communication. In order to unify the computer systems there was a need to develop norms and standards which in turn resulted in establishment of international organisations like International Standard Organisation (ISO), Manufacturing Automation Protocol (MAP), and Technical Office Protocol (TOP), etc. In Europe, in the United States of America and Japan (1980-1984) majority of the industrialists realised the importance of CIM and its benefits. They thought that integrating a computerised system into their production could be an ideal and appropriate concept. In the early seventies there was a short investment in computer-based production, which was not able to cover overall information technology needed for the market. However, this investment grew very faster since then and in 1988 it was up to 68 billion USD. At the same period the share of the world market taken up by computer-based production and inventory control and the management information system amounted to 8.3 billion USD and the investment on the Programmable Logic Controllers (PLC) and the Local Area Networks (LAN) was about 7.7 billion USD [3].

1.1.2. The classic interpretation of CIM

CIM is the concept of a completely automated factory in which all the functions of a company (design and methods, production, administration, accounting, marketing, etc.) are integrated and controlled by computerized systems. CIM enables all those involved in the company to use common data shared through the same database, thus improving responsiveness and efficiency when faced with fluctuating markets [3]. *Tóth, Tibor* [38] in his lecture draft presents "The range of concept and sphere of authority of CIM" and defines "CIM" as efficient company management philosophy and strategy for improving the quality of products and technology processes as well as business flexibility of production. Unfortunately it has been very difficult to define CIM; many different definitions in the literature attest to this statement. However we may understand CIM is literary as a management philosophy in which the functions of design and manufacturing are rationalised (bring into conformity by reason) and co-ordinated using computer, communication and information technologies. According to literature overview *rationalised* in this context means [28]: <u>*The entire [manufacturing] system, from product definition and raw material to the disposition of the final product, is carefully analysed such that every operation and element can be designed to contribute in the most efficient and effective way to the achievement of clearly enunciated goals of the enterprise*</u> [5].

CIM is defined as a standard model, which its fundamental objective is to propose integration of generic applications, which are usual characteristics of manufacturing system. To achieve this fundamental objective, there is a need to establish a certain number of standards and norms with the responsibilities of different international organisations. A number of organisations involved and collaborating in working out standards are, as European Strategy Program for R&D and Development in Information Technology (ESPRIT), Computer Aided Manufacturing International (CAM-I), Data transfer standards in CAD graphics (IGES, VDA, SET, STEP) and Electronic Data Interface (EDI), etc. As far as the plant is concerned, there are six major components (Fig.1.1.)[5]:

1. Computer-Aided Design (CAD). CAD encompasses computer-aided graphic, computer-aided drawing and drafting, and computer-aided design. This latter area is allowing for analysis as well as graphical representation. For example animation can be utilised to show the damping effects of the suspension design of car in given the road conditions. The stress analysis is also involved in this category (Finite Element Method, etc.).

2. Production Planning & Control and Scheduling System (PPS/PPC). PPS/PPC governs the acquisition of all the materials needed for product

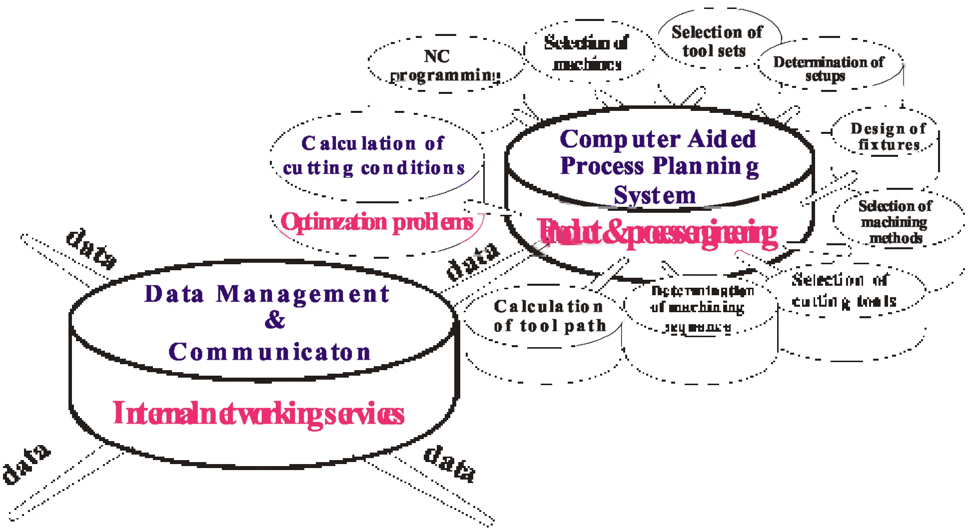


Fig.1.1 Structure of Computer Integrated Manufacturing System (CIM)

manufacturing. After receiving the customer order through the market, PPS/PPC considers all the requirements needed to produce the product. These requirements are: cost accounting, forecasting capacity adjustment, Material Requirement Planning (MRP-I), Manufacturing Resources Planning (MRP-II), as well as purchasing, shop floor control and sales order & control. PPS/PPC ensures that customer needs are satisfied. PPS/PPC is the most important area in manufacturing system and this area actually controls the manufacturing system as a whole.

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

4. Computer-Aided Manufacturing. Many people think that computer-aided manufacturing is for chip-cutting parts. This is not the case, as cannot be stressed so forcefully. Electronic manufacturing has to follow the same CAM practices. For example assembly of parts into a circuit board is no different in concept for assembly of a turbine engine.

5. Computer-Aided Storage and Transportation. The automatic storage and retrieval of materials, components, and finishing goods is the fifth component of CIM. This includes not only incoming materials and finished products but also the temporary storage of work in progress.

6. Data management & Communications (net work system). Allows all the components to work as an integrated system, as demonstrated by *the data management and communications component*. The function of this component is the information flow in CIM, which is the major problem to be handled effectively. Finally, to allow all the components to work in a system, we have to integrate the five components with a network system as exemplified by the *data management and communications,* the 6-th component of CIM [6]. Standards have been evolved for this function, but the information flow in CIM is still a major problem to be handled effectively.

The author at this point would like to draw the attention of the readers that the structure which is demonstrated has got its infrastructure based on *system approach* which is defined as " a technique that allows a large, complex system with interacting components to be analysed and improved", in hierarchy. The steps involved in the system approach generally follow those given by *Bedworth and Baily* [4].

In the systems approach comments, it is necessary to break the system into components for initial analysis. In fact, this overall system approach would be applied to the six major components just discussed, including the component of data management for communications. Analysing the entire system, as a whole would initially be far too complex as just mentioned, then individual component analysis has to be accomplished. However, component analysis has to be done in light of the entire system. After the components have been analysed, integration into the system is mandated. With CIM system, this is accomplished through networking scheme with smart manufacturing database that can handle design, production and planning. All of the various functions included under umbrella of computer-integrated manufacturing are indicated in a matrix presented by *Adlard, Edward J.* [1]. As a result of above-mentioned interpretation of CIM the author's idea of Computer Integrated Manufacturing (CIM) may be defined as follows:

Computer Integrated Manufacturing (CIM) is the use of Computer Systems and Automation Systems to operate and control production. This definition splits production into two separate activities: the *Information Processing* performed by *Computer Systems* and the *Physical Activities* performed by *Automation Systems*. Information Processing tasks include: the design of components; planning the production of the components; controlling the operations in production and performing various business related functions necessary for a manufacturing establishment.

A wide range of devices, often automatically controlled, including; Machine Tools, Assembly Stations, Robots, Material Transfer Systems, Automated Material Handling and Storage Systems and Inspection Systems perform the Physical Activities for Quality Control. These devices actually alter material and move it about a factory and take measurements and ultimately feed back information to the human operators. They automate the physical activities.

In the same way the devices of the shop floor automate the physical activities, the computer systems automate the information processing functions; providing that these different functions are closely integrated. To achieve CIM, all aspects of the manufacturing establishment must be integrated so that they can share the same information, communicate with one another and provide a global picture as to the state of the entire manufacturing facility at any time.

1.1.3. New approaches to CIM

The new approaches to CIM are the replacement of traditional (closed system, standardized integration, autocratic management, mechanistic model of worker and passive formalized training approaches) by new organizational structures (open system, flexible integrated system, horizontal management style, and an active self-learning environment) characterized by emphasis on self-management [13].

1.2. Production Planning and Control

Production planning translates the sales into forecasts by part number. It means that what product should be produced considering the constraints (e.g. technical facilities and personal resources) and the period, which is suitable for producing this product. It should be reminded that the chief activities of marketing are forecasting sales, advertising, and estimating future demand for existing products. Selling the product is the primary interest of marketing. Promotional activity, involves advertising and customer relations. Customer service is a critical function for any manufacturing company. Thus, marketing provides information and services as well sales forecast of future demand, sales order data, customers quality requirements, customer reliability requirements, new products or modifications for existing products, customer feedback on products and customer service (repair or replace defective products). After translating sales into forecasts, the authority to manufacture the product is translated into *master production schedule*, (a plan that specifies how many of each type of end product must be produced in each period of the planning horizon) a key planning document specifying the products to be manufactured, the quantity to be produced, and the delivery date to the customer. The master schedule is converted into purchase orders for raw materials, orders for components from outside vendors, and production schedules for parts made in the manufacturing system. *Production control* develops the timing and co-ordination to ensure that the delivery of the final product meets customer demand. Because of the complexity of the job shop manufacturing system, production is not controlled very well; therefore, many other control functions are needed. The scheduling periods used in the master schedule are usually months. The master schedule takes into account the production capacity of the plant (how much can be built in a given period of time). The capacity of a job shop is tremendously variable and flexible and is not well controlled. Because of this characteristic, larger quantities of products are often requested in violation of the master schedule. Based on the master schedule, individual components and subassemblies that make up each product are planned. Raw materials are ordered to make the various components. Purchased parts are ordered from vendors. The frequently used *Material Requirement planning* (MRP) is discussed later.

The next task is *production Scheduling* in which start dates are due dates, which are assigned for various components to be processed through the factory. Many factors make the job-scheduling task complex. The number of individual parts can be in the thousands. Each part seems to have its own individual process route through the plant. Parts are often routed through dozens of separate machines in many different departments. The number of machines in the shop is limited, and machines are different, perform different operations, and have different features, capacities. In addition to these factors, parts become defective during processing, cycle times vary, machines break down, and operators expand job times to fit the time available. All these factors destroy the validity of the planning schedule and require (in the classical system) huge amounts of resources (lots of people and paperwork) to manage all the exceptions. *Dispatching* is the production planning, and control function requiring voluminous paperwork whereby individual orders such as order tickets, route sheets, part drawings, and job instruction are sent promptly to the machine operators. The finished product is either shipped directly to the customer or stocked in inventory. *Inventory control* is used to ensure that enough products of each type are available to satisfy the customer demand. However, competing with this objective is the company's desire to minimise its financial investment in inventory. Inventory control interfaces with marketing and production control since co-ordination must exist between the various product's sales, production, and inventory levels. Although none of these functions can operate effectively without information about what the others are doing, this information is often missing or out of date. The production planning and control department often does inventory control [29].

1.2.1. From the PICS conception to the up-to-date computerised PPS-MRP systems

In the end of 1960s IBM the American company in the United States of America introduced the first PPS under the name of PICS, which is the abbreviation for Production Information System. Of course it was the first approach towards production planning & control and scheduling system in all over the world. To develop such a system, it was necessary to create a correct and clear model in order to be understood, as a theoretical concept to satisfy the manufacturers needs of production. According to the case study the suggested system had a model, like a cycle wheel with eight sectors actuated in it. The general database was located in the middle of the system where there were eight subsystems around it. The first subsystem belonged to the technical data, the bill of material and the general technical documentation for an enterprise. The Production Information Control System (PICS) was only a concept without realising the use of computer. In spite of the fact it was a successful system from theoretical point of view, but in reality behind the system there was no a generalised theory, but only an empirical approach [39, 40]. The up-to date Production Planning and Scheduling (PPS) describes the use of computer-aided systems for quantitative, on schedule and capacity just planning, cause and supervision of the order handling of the offer processing up to the dispatch. In order to control inventory within the job shop, a computerised system called Material Requirement Planning (MRP) was developed. Material Requirement Planning (MRP) is the process of comparing the master production schedule with on-hand and in process inventories and orders to determine how many of each item in the bill of materials (BOM) must be manufactured.

1.2.2. A PPS-MRP system localised into CIM environment

Production planning & scheduling focuses on scheduling individual production units or shops. A production unit is a production department, which on short term is self–contained regarding the use of resources. The production unit is responsible for the timely production of a specific set of products (Fig.1.2).

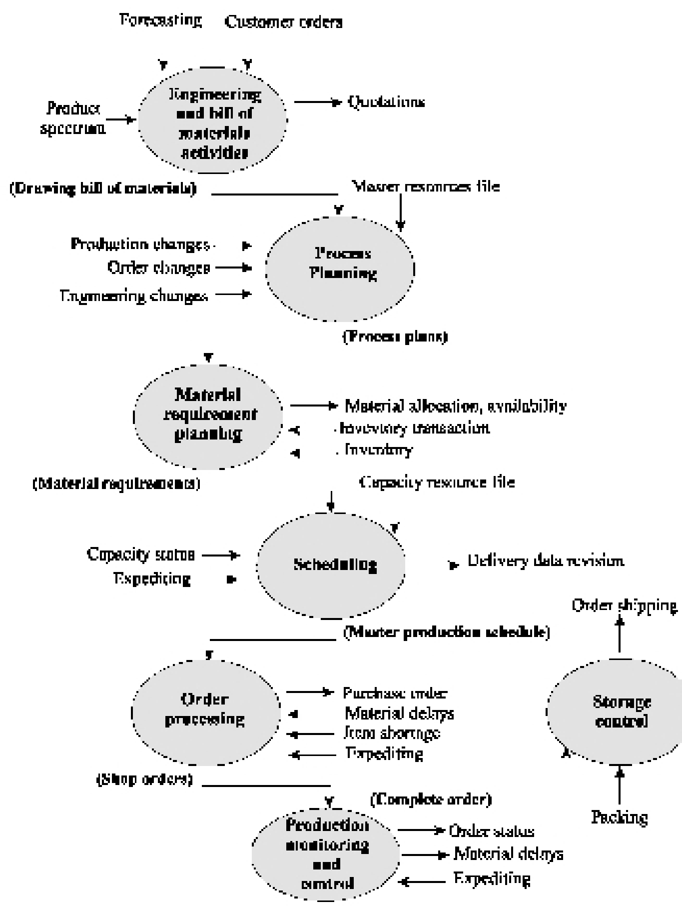


Fig.1.2. Levels of PPS-MRP localised in CIM environment

The input of scheduling comes from the planning function (for example an MRP standard software package) and consists of material requirements in time. The scheduling function can then be stated as follows: for each capacity resource, determine the points in time in which manufacture will be executed, under the following constraints: Finite capacity resources, precedence relations (routings), and start– and due–dates of work–orders. The scheduling function should optimise certain logistic goals, (e.g., resources utilisation, set–up times, stock costs, throughput times, service level). Also, the sequence in which the work–orders are produced in the production unit has to be determined. This decision is referred to as sequencing. However, when a schedule has been made, a specific sequence is implicitly defined by the schedule. The result of the scheduling function, the schedule, is transferred to the shop floor. The scheduler monitors the progress of work–orders through the shop.

1.3. Computer Aided Process Planning (CAPP) for Discrete Manufacturing

Computer Aided Process Planning aids in creation of process plans in manufacturing. One of the inputs of this process is a CAD-model of the work-piece to be created. The result of the process is a detailed process plan from which the work piece can be created. By definition process planning is preparing a set of instructions, which describes how to fabricate a part or construct an assembly, which may satisfy the customer order. These set of instructions include the sequence of operation, the selection of machines, tools, materials along with process parameters, set up time and many various stages, which are used in completion of a product. It means that once the parts have been determined for which CAM is to be applied- say, through group technology- the method by which these parts are to be manufactured has to be evolved. Considering the significant importance of the process planning it may be very complex and time consuming job because it may require a lot of data as well as several people may participate in developing a process plan, because only one person may not have broad and extended knowledge and expertise in developing a plan for the required process. The process planning can be much more complicated by the fact that a part to be produced *correctly* and *economically* is not an easy task.

1.3.1. Evolution of the independent CAPP systems

Process planning emerges as a key factor in CAD/CAM integration because it is the link between CAD and CAM. After engineering designs are interpreted, either on paper or electronic media, the process planning function converts the designs into instructions used to manufacture the specified part. CIM cannot occur until this process is not automated; consequently, automated process planning is the link between CAD and CAM. Automated process planning provides a means to facilitate the communication between design engineering and the other areas of manufacturing system.

1.3.2. A CAPP system localised into CIM environment

As it was mentioned in sections 1.3 and 1.3.1, Computer Aided Process Planning (CAPP) evolves the sequence of operations required to manufacture a part, the time required to accomplish the operations, the machines and tooling required, and evaluates tolerance stacking problems that accrue from multiple cuts and/or multiple components that comprise a part. The process planning function can ensure the profitability or non-profitability of a part being manufactured because of myriad ways (more than thousands ways) in which a part can be produced. The process planning information feeds into the Material Requirement Planning (MRP) analysis as well as into shop floor scheduling in CIM environment, so that detailed schedules can be evolved for machines, tooling, fixtures, people, material handling, testers, and materials.

1.4. The objectives to be targeted in the Dissertation

In producing the goods manufactured by the engineering industries, ideas originating from *management* and the different departments responsible for preparatory activities and actions of production (e.g. design, production planning, production engineering etc.) need to be communicated to those working on the *shop floor* . Computer Aided Design (CAD) and Computer Aided Manufacturing (CAM) and the link, which integrated them namely

Computer Aided Process Planning (CAPP) is the key point in improving productivity to allow manufacturing enterprises to maintain a competitive edge, as there will no a guarantee for any company or nation to be sure of having a dominant position in a specific market if the importance of CAPP is not over stressed in CIM environment. In order to carry out the entire process to be accomplished in as economical manner as possible, *cost accounting* and *time* have to be brought into the picture and information from these groups is used as a key in design and manufacturing decisions. These *two entities* constitute the main starting point of the Thesis, as without considering them it is quite impossible to accomplish the entire process in *economical manner*, furthermore any economical aspects need *optimization procedures*. The optimization procedures in this Thesis are based on *optimum determination of the technological parameters*, *optimum determination of the rate of stock removal factor* and *optimization o f the total cost of given operation*. In this respect, as a result of the justification of CIM system, significant relationships between technical and managerial data can be established.

Computer Aided Production Planning & Control (CAPC)

The APICS (American Production Inventory Control System) Dictionary defines CAPC as [21]:

- The function of setting the overall levels of manufacturing input/output and other activities to best satisfy the current planned level of sales (sales plan and/or forecasts), while meeting general business objectives of profitability, productivity, competitive customer lead times, etc., as expressed in the overall Business Plan.

- The sales and production capabilities are compared and a business strategy that includes a production plan, budgets, financial statements, and supporting plans for materials and work force requirements, etc., is developed.

- One of its primary purposes is to establish production rates that will achieve management's objective of satisfying customer demand, by maintaining, raising, or lowering inventories while usually attempting to keep the work force relatively stable.

- Because this plan affects many company functions, it is normally prepared with information from marketing and co-ordinated with the functions of manufacturing, engineering, finance, materials, etc.

2.1. The interpretation of CAPC

Inputs to the CAPC are ***primarily*** demand management. This encompasses order entry, order promising, forecasting, inter plant transfers, exports, service parts, etc. One must take into account the number of selling days during the month the trends, the tradition cyclic nature or seasonal demands the business before arriving at a demand figure for each month. In addition the aggregate on-hand balances for each product category must be known at month end together with the actual sales and production for the past month. Once these and the true demand, with regard to shipments, per month is known and agreed upon with marketing the CAPC can be constructed. The CAPC should project out into the future at least as far as the lead-time to significantly change our capacities. This could range from a couple of months for a fairly unskilled labour intensive business to a couple of years for a heavily capital intensive organisation. We also need to decide on an inventory policy for each of our product categories before proceeding with the CAPC (e.g. we wish to reduce stocks to manageable levels. Then we have to build ahead for seasonal demands, planned machine maintenance programs, special offers, etc.). Available capacities will need to be known per month. Information such as planned maintenance programs, utilisation, efficiencies, number of production days per month will need to be ascertained so that a level production plan can be created to avoid large swings in labour requirements as well as overtime and short time. In the end CAPC must be ascertained to see if total sales, inventory and capacity utilisation objectives are going to be achieved or not.

2.2. Readiness for delivery, Stock-level, capacity- utilisation

Considering the task of CAPC independent from its complexity, consequently to determine external and internal orders inside the given enterprise we may suggest three main theoretical factors as follows, (Fig. 2.1.), [24, 35]:

- Readiness for Delivery (RD)
- Stock Level (SL)
- Capacity Utilisation (CU)

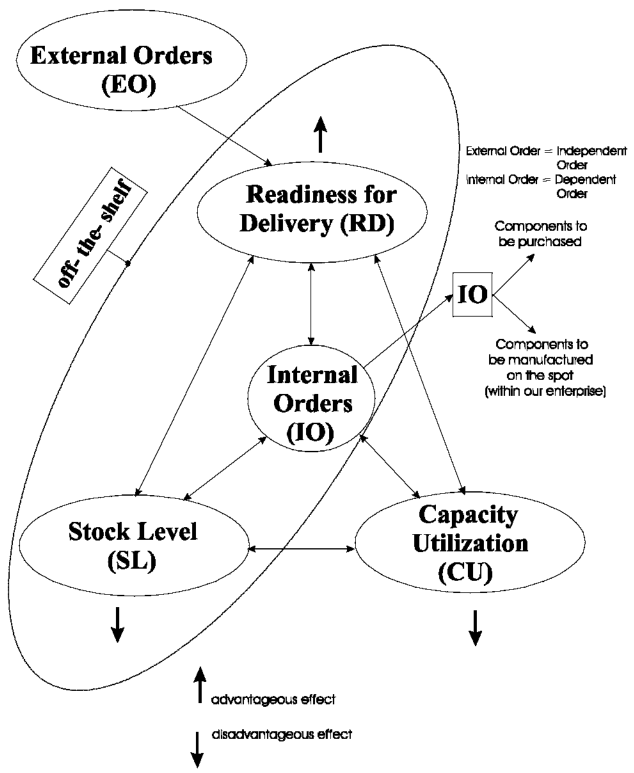


Fig.2.1. Production Triangle

As is shown in Fig.2.1, the first main factor is the ***Readiness for Delivery (RD)***.

Considering the type of the products for the optional number of orders the <u>*Stock Level (SL)*</u> is the second main factor and it is related to all kinds of stock types and the third main factor is the <u>*Capacity Utilisation (CU),*</u> which is related to all capacity types of the enterprise. These three main factors produce <u>*a new concept*</u>, which is called the "<u>*Production Triangle*</u> . The mathematical model can determine the relationships among the factors of the "production Triangle".

Defining Readiness for Delivery (RD), let's suppose that Jan 2nd 2000 is the starting time of our operation year on X-axis co-ordinate belonging to the time horizon (Fig. 2.2.) and somewhere on this axis we have got an External Order (EO) at $t_{1,i}$. After some time at $t_{2,i}$ we decide to accept the order considering all the possibilities of the enterprise in order to fulfil the running of the given order and we calculate the delivery of the order at time $t_{3,i}$.

Then manufacturing and assembly time which is between $t_{3,i}$ and $t_{2,i}$ is $\Delta t_{32,i}$. We can show these relationships by the following:

$$(RD)_{(EO)_i} = \frac{1}{\Delta t_{32,i}} \left[\frac{1}{day}\right]$$

which is called <u>*Readiness for Delivery*</u> (RD).

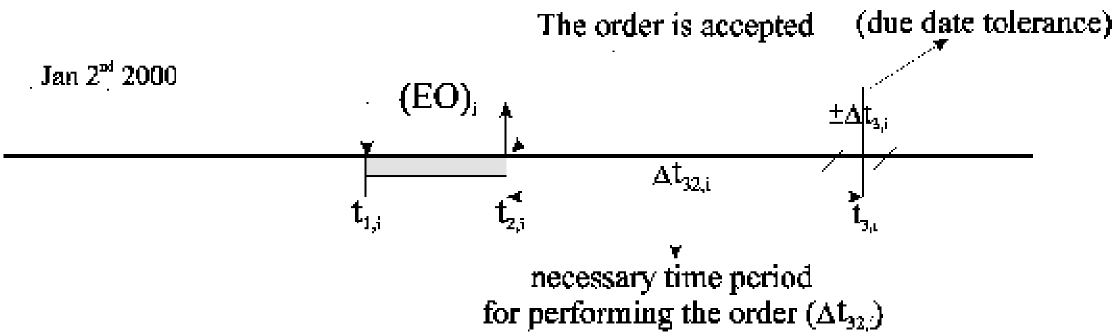


Fig. 2.2. Interpretation of the concept "Readiness for Delivery"(RD) using a demonstrative example

<u>*Stock Level*</u>: All types of stock should be taken into account (e.g. blanks cast pieces rolled stocks intermediate pieces, spare parts, purchased parts, and bearings, etc.).

<u>*Capacity Utilisation*</u>: It is expedient to find so-called homogeneous workplace capacities and to classify our homogeneous workplaces. What does

homogenous mean? The basic idea of "Production Triangle" comes from a new CAPC system named *KYBERNOS* (software) [16,22], which is applicable in enterprises and has got the following major characteristics (Fig.2.3.).

- The system is based on a mathematical model which is suitable to be applied both in traditional and automated manufacturing systems;
- It meets the needs of the enterprise independently from its size and special profile;
- The system supports industrial introduction by means of self-learning methods connecting special areas of the enterprise (e.g. designers, process planners, manufacturing dispatchers) carrying out their usual works without any change of workstations and terminal of the system (PC-network, several workshops) and the average period of an introduction is not more than six months;

- The proposed *KYBERNOS* system is utilised as a subsystem in CIM environment. Its user interfaces and data interfaces are able to communicate with other Caxx subsystems (CAD, CAPP, CAM/CAST, etc.) and users as well.

The system is under implementation and /or introduction at several enterprises and its introduction strategy takes into account the simultaneous work of six special areas namely sales, purchasing, storage, manufacturing scheduling and release of job orders, design engineering and accounting.

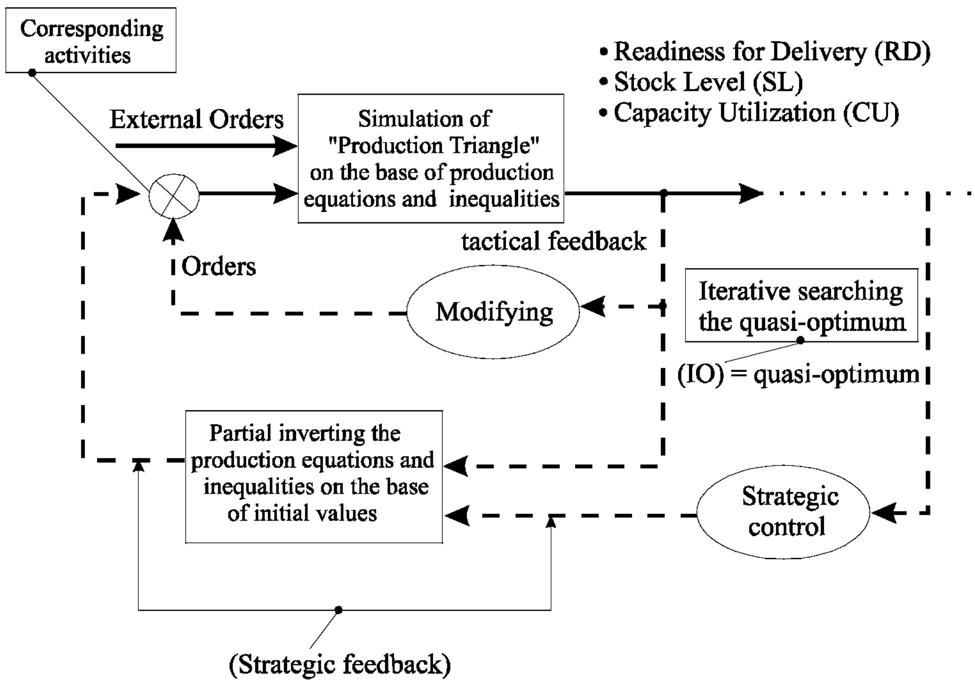


Fig.2.3.The anticipating control loop for CAPC (KYBERNOS)

Computer Aided Process Planning

As is shown in Fig.3.1., planning and control of discrete part manufacturing is a very complex function group. For describing it a three-level modeling and optimization structure is required. The levels are as follows [41, 42]:

- *Process planning level*: The process planning function defines how products can be made, including the overall process plan defining the possible sequences of operations to manufacture a product and the detailed operation process planning, prescribing the parameters of the individual manufacturing steps. In traditional manufacturing systems, process planning provides shop floor control with a single sequence of operations to be executed for each product. Recently, process planning is considering more flexible solutions, based on the use of alternative routings, and alternative machine allocations.

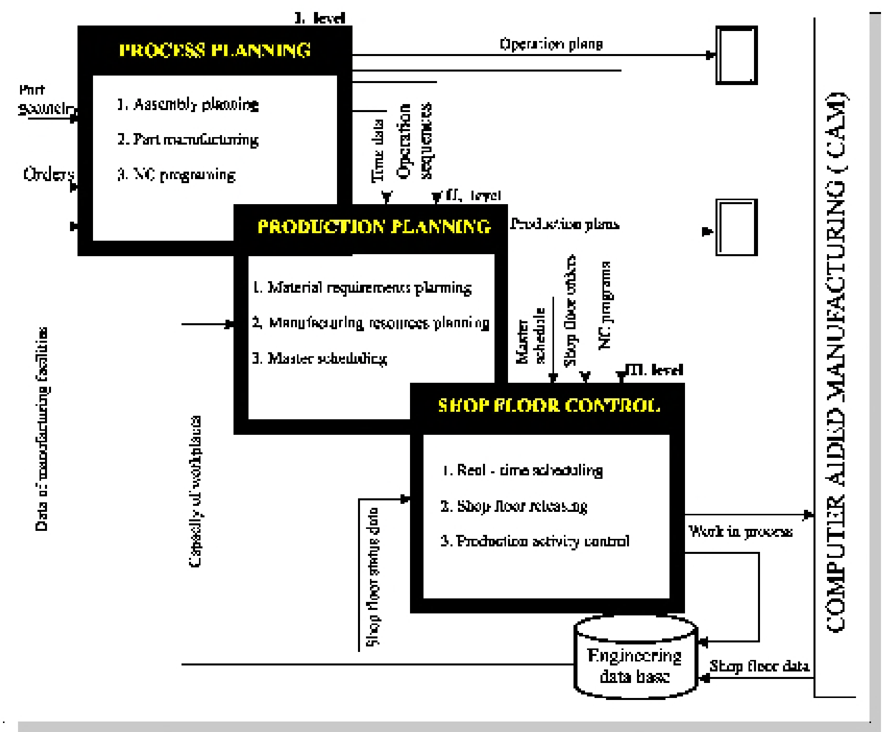


Fig.3.1.The three level model of production management

The use of alternative routings, modelled (e.g. by precedence graphs, dynamic precedence graphs or Petri nets) enables shop floor control to select the best sequence of operations depending on the machine load and unforeseen disturbances. The use of alternative resources for an operation gives similar opportunities. Process management also includes operational aspects of manufacturing system design, lay outing and configuration. Depending on the flexibility of the manufacturing system, the manufacturing system may be adaptable on short term and short-term modifications and set-ups time are managed by shop floor control.

- *Production planning level:* Optimization of scheduling, inventory and machining capacity utilization.

- *Production control level:* At this level typical performance criteria in a manufacturing context are: the *throughput* is defined as the number of orders the manufacturing system finishes per time unit; the *work-in-process* inventory (WIP) is defined as the number of orders in the system which are not finished yet; the mean order *flow time* (lead time) is defined as the difference between the order finish time and the order start time); and the mean order *tardiness* (The tardiness is the difference between the order finish time and the due date, if this difference is positive. Otherwise, the tardiness is 0.).

At this three levels, the applied models and resources, as well as the objective functions and constraints are different. An additional serious problem is that the three functional models are connected to one another in time and functionally in such a way that more and more complicated and aggregated objective functions appear in the lower level models. This reason is a day-to-day problem for shop floor control level where there is no solution meeting all the constraints at any control decisions of the dispatcher.

3.1. Integrated process planning and control

There are numerous suggestions in the literature for solving the problems of integrated process planning and production control [19,18]. Among them the COMPLAN project supported by ESPRIT is the most comprehensive one [26]. The different approaches suggested are as follows [3, 42, 43, 11, 48]:

"Non-linear" Process Planning (NLPP)

The controversial name covers, in reality, preparation and application of alternative process plans for supporting shop floor level decisions. In this approach, the usually linear process plan sequence is enhanced to include also manufacturing alternatives or possible changes in manufacturing sequence. Several alternative routings or sequences of operations are combined in a net structure, so called non-linear process plans (NLPPs). The required initial process planning effort is high but it later provides full flexibility to optimally load resources and also to re-allocate jobs in case of unforeseen disturbances.

Non-linear process planning has been investigated in the FLEXPLAN project and has now within the COMPLAN project been realized in a fully functional software system. In an integrated system process planning must not only follow technological criteria but also consider logistical objectives. This is achieved by representing and storing feasible manufacturing alternatives in a net-shaped process plan (NLPP). This requires higher initial effort for process planning but has certain advantages especially with respect to later commercial application as compared to the dynamic or just-in-time approaches to process planning. This approach allows to re-use plans and planning information and updates them continuously with workshop feedback data. A manual control of the planning process is possible at all stages. The accumulated database of process plans and manufacturing alternatives allows also a variety of investigations, statistics and evaluations on effectiveness and efficiency of manufacturing.

Dynamic Process Planning (DPP)

Dynamic Process Planning (DPP) aims at full integration and concurrence between process planning and scheduling activities. This approach does not determine the complete operation sequence and the corresponding resource allocation at once. Every time an operation is finished, the current state of the work piece and the actual workshop situation are re-investigated to determine the best next operation and suitable resource to continue manufacturing of this piece. Some higher level planning has to be carried out to ensure that this approach does not frequently generates dead ends. This approach provides a maximum of flexibility for reactions and avoids all unnecessary planning effort on alternatives that are not used. Disadvantages are that only local sub-optima can be achieved because only a very limited time horizon is considered at the time of decision making. The overall planning effort is high because previous process plans cannot be re-used. Dynamic process planning is an issue that has been talked by *Iwata* and *Koshnevis*. Laboratory implementations have been realized, but this approach has not yet proven its feasibility in a full grown industrial application.

Just-in-time Process Planning

Instead of re-using previous process plans or creating process plans weeks before manufacturing, Just-In-Time process planning is started just before the first manufacturing step is about to commence. This allows taking the actual workshop situation into account for decision-making on the resources used for manufacturing a part. This approach has been investigated and realized in the PART system at the University of Twente , The Netherlands. The PART system has evolved into a commercial software system that is distributed by CONTROL DATA. The commercial DTM-CAPP system, distributed by *Somatech*, has obtained similar features. Advantages of this approach are that, a well balanced workshop load can be achieved and that it is not required to plan alternative routes in detail that are later not used. The results are a conventional linear process plan that can easily be exchanged with existing MRP or workshop control systems. However, at the time a process planning session is started for a complex part with many operations, the actual workload is hardlypredictable. The load which will be added by simpler parts with fewer operations and a thus shorter throughput time, is not known, since these parts will enter the process planning only at a later phase. In a mix of complex parts and simpler parts, it is thus not possible to achieve a planning optimum. The re-use of process planning information from previous manufacturing is also not possible (a part may be manufactured each time in an other way) and the problem of re-allocation of jobs in case of disruptions in machine availabilityis also not addressed [10].

Closed-loop Process Planning (CLPP)

On the base of real shop floor status data, making regenerated process plans using a CAPP system.

Distributed Process Planning (DPP)

Distribution of process planning into a preliminary and a final phase. The latter can only be generated in full knowledge of the real data.

Adaptive Control (AC)

Operations can be controlled on the base of the data measured directly on the given machines. Shop Floor Control determines the tactical goals of control.

Each of the mentioned approaches has some disadvantages and application constraints. Alternative process plans require large-sized databases and new decision supporting systems. Closed-loop process planning requires high-level information management capabilities with Group Technology supplies, variant principle based process planning and the computer network available. The sphere of activity of distributed process planning is narrower in comparison with those of the previous approaches. Finally, as regards adaptive control, it can only be applied in a restricted way according to its sensor and real time data processing demands.

3.2. Robustness as a significant criterion for planning discrete manufacturing processes

The concept of *robust control* appeared in Process Control Theory in the eighties and it has been of great importance. One of the old problems of Control Theory is the fact that the controllers designed in a deterministic way are optimal only for a defined *control structure* according to some kind of criterion (in most cases *the method of minimum squares* is used for the deviations), but in the case of basic signal changing, controlled plant changing or appearance of a disturbing signal, optimum functioning is not guaranteed.

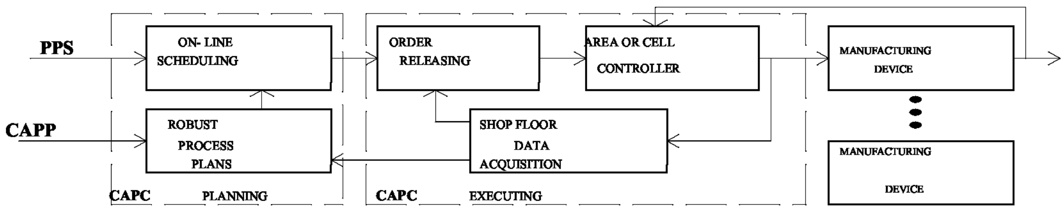


Fig.3.2. Planning and executing functions in production control [15]

The generalised model of manufacturing system can only be described by means of complicated, multi-variable discrete *state equations*. The dynamic state of manufacturing systems can usually be affected by such intervening (controlling) decisions, parameters of which are mostly discrete finite sets or such parameters which are subordinated to homogeneous (one-variable) or in homogeneous (multi-variable) constraints. Control of manufacturing systems also includes planning and executing functions. *Planning functions* generate technology and production plans in preliminary forms. *Executing functions* make decisions of real-time production control (Fig.3.2.).

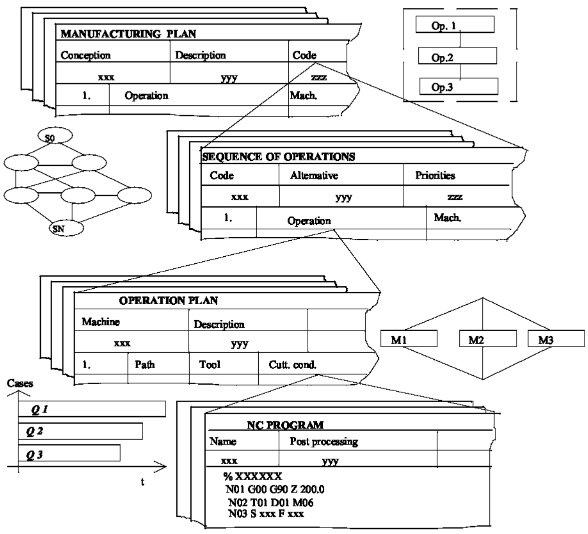


Fig. 3.3. Hierarchy of robust process plans [15]

An integrated Production Management System, which is capable to adapt to uncertainty and, at the same time, to optimise technology processes on the base of production objective functions, can apply *two* fundamental methods. *One* of them is the application of robust alternative technology plans and production plans; the *other* is adaptive re-scheduling method for production control. Hence, robustness of technology planning rests upon the alternative ("non-linear") process plans interpreted in a wider sense. Alternative technology process plans form a hierarchical data structure (Fig.3.3.), [35]. At the highest level of hierarchy the variety-set of operations planned previously is placed connecting with sequence relations. Technological graphs and *Petri-nets* are suitable for representing them. The classic optimisation task for planning the sequence of operations can be modelled by means of *Dynamic Programming* and *Travelling Salesman* method, however, finding the most advantageous sequence of operations is fairly difficult in the case of multi-operation parts. For the searching tasks to be executed on large-sized graphs, in addition to *Branch and Bound* method, *genetic algorithms* can recently be applied successfully [47]. Genetic algorithms are especially suitable for supporting the robust technology planning approach because the current alternative process plans can easily be arranged into qualified groups by means of genetic populations. These qualified process plan groups can support decisions of Shop Floor Control in an effective way. A following level of alternative technology plans includes the alternative allocation of operations to workplaces (machines, equipment). As a result of a current allocation, certainly, the time and cost of the operation in question will also change. From the point of view of production planning these data are important for that reason because the current PPS system handles the functions of Master Scheduling (for a given shift), utilisation of capacities, performance of delivery deadlines and minimisation of production costs depending on these data. Real-time production control is frequently constrained to utilise an alternative workplace (machine) because the machine previously taken into account has broken down or it is converted into a bottleneck, by chance the tool, fixture/jig or NC-program are not available for the planned operation. The alternative workplaces belonging to any operation can be arranged in accordance with different priorities and can give database of a decision supporting system [41,42].

3.3. The role of technology parameters in robust process planning

Determination of the technological parameters of cutting processes, taking the manufacturing aim and economical aspects into consideration, is one of the important and systematically returning task of production engineering. An appropriate utilization of the production means being disposable and fulfillment of part quality requirements depend upon the cutting conditions to a great extent. Determination of optimum cutting parameters is of a great importance especially for NC/CNC machine tools and FMSs for which the technology processes have to be planned in detail, independently of the number of the parts to be manufactured. As is known that increasing the intensity of cutting parameters results in decreasing the costs connected with the machining time of the given operation (or sub-operation). At the same, in consequence of increasing the loading and wearing of the tool, it yields an increase in the tool costs. Studying the two contrasted effects, it is easy to see that the appropriate choose of cutting parameters means finding the reasonable compromise. From the mathematical point of view this necessitates setting and solving an optimization problem. To solve this task successfully, in addition to an available computer and software tools, a theoretically well-established mathematical model, an up-to-data solution method and a reliable database are required. A disadvantage of majority of the sophisticated solutions published so far is the use of relative difficult methods of Operations Research. These are general methods and are not able to utilize the special features of the given task to an appropriate extent. From the published special and effective procedures the *Somló s* method (1979) is excellently applicable. He gave a very clear and deep analysis from the mathematical model of cutting processes resulting two theorems which regard to the place of the possible optimal points and an algorithm to find the local optimum. In case of stepped revolution numbers and feed rates some iterative algorithms proposed by *Tóth, Tibor* (1976) can be also advantageously used.

3.3.1. Traditional approach to the determination of optimum cutting conditions

In most cases of production planning and scheduling the required production time for any specific task is known in advance. However, in practice, it is possible to vary production speed by altering the manufacturing conditions. An important example of this is metal cutting manufacturing processes. Research on optimum cutting parameters goes back to 1907 *(Taylor, F. W.)*. Since then, this problem has been approached using different methods. Different optimization methods, ranging from simple classical methods to sophisticated constrained optimization techniques considering the probabilistic nature of problem and geometric programming has been reported to be successful. Analysis of single and multi-pass turning under practical constraints has been done using minimum production cost or time criteria. Since the results obtained by using these two different criteria are always different, *Okushima* and *Hitomi*, *Wu* and *Ermer*, *Boothroyd* and *Russek* have used a maximum profit rate, which yields a compromise results, in subsequent investigations. However, in practice profit rate is not a steady variable, therefore this criteria does not always produce realistic results. Some methods reported in the literature to solve optimization problems for machining conditions include performance envelope, linear programming, Lagrange multipliers, geometric programming, dynamic programming, graphical methods and artificial intelligence. *Walwekar* and *Lambert*, *Ermer* and *Petropoulos* stated that geometric programming method is more powerful than other optimization methods in determining the optimum machining conditions when the solution is restricted by one or two inequality constraints. But they also pointed out that as the number of constraints increases another optimization methods should be employed together with the geometric programming. Cutting rate-tool life function theory studied by *Ravignani*, *Tipnis* and *Friedmann* [31,34], has permitted determination of machining economic optima for machine tools by means of two variables: the metal removal rate and the tool life. Application of this research to a machine tool is limited by cutting constraints, which depend on machine tool and work piece characteristics. Yet tool life may be submitted to large variations caused by workpiece heterogeneity. These variations may be a disadvantage in batch production when tool life change is determined *off-line* to optimize cost production. *Richard, J. , et al.* have studied an adaptive control system for CNC machine. In their approach tool wear is measured during machining and the system maintains tool life constant by means of cutting speed (v) variations, thus the cost function is optimized *on - line* in the constraints domain. The principal advantages are control of machining time for batch production and the maintaining of constant production costs which improve production planning. A simple method to understand and apply to the optimization problem was published and explained by *Kiliç*. This method is particularly applicable to situations where the available machine speeds and feeds are stepped. It searches the optimum point along the constrained border, reaching the optimum in a number of steps equal to the sum of the number of available feeds and spindle speeds. Objective function has only two variables (feed rate and cutting speed) but it is not possible to explicitly express one of the variables in terms of the other. *Kiliç* and *Çogun*, developed a graphical model in order to draw the constant value of the objective function and determine the optimum point. It was developed for single pass applications [25]. Since multi-pass operations for economic reasons, recent efforts have made to determine optimal machining conditions for multi-pass operations. *Iwata, et al*, applied dynamic programming for multi-pass turning operations. This method does not require equal depths of cuts for passes. *Hinduja, et al.* defined the objective function and constraints in terms of depth of cut and feed rate and evaluated finish pass and rough passes separately. The summation of the depth of cut of the rough passes is not always equal to the total depth of cut and the methods introduced to equalize these values may not always give the optimum solution. They suggested using the maximum allowable depth of cut of the tool for the finish pass, which is also open to discussion. In the work of *Cakir, M. C.* and *Gurarda, A.*, total depth of material to be removed including finish pass and rough passes are cut with the same tool. This volume is divided into sections and each section is threatened as a single pass operation by taking the constraints maximum and minimum feed rate and speeds available, cutting power, tool life, deflection of work piece, axial pre-load and surface roughness into consideration. In this work optimum values of machining parameters were found by using a search method in the feasible region, which calculates the minimum cost value and corresponding optimum feed rate and cutting speed values. After applying this method to each possible section and storing them in a matrix form, dynamic programming techniques were applied to minimize the objective function *Boothroyd* and *Rusek* used a maximization criterion for the rate of profit.

Philipson and *Ravindran* employed different single-objective as well as bi-criteria mathematical models. *White, Lee* and *Kwak* used computer simulation. *Hati* and *Rao* considered three objectives: machining cost, production rate, and profit rate. *Ghiassi, et al.* used a multiple-objective linear programming technique. *Tabucanon* and *Mukyangkoon* presented interactive goal programming [45]. *Malakooti* and *Deviprasad* used an interactive multiple-criteria approach for parameter selection in metal cutting. Their objectives were to minimize cost per part, machining time per part, and roughness of the work surface, simultaneously. They utilized a gradient-based multiple-criteria decision-making heuristic approach for selecting optimal parameters in metal cutting. *White* and *Houshyar* presented single-variable optimization techniques in which cutting speed was the variable under consideration. A single-stage machining model was developed that deals with machining times and cost as functions of speed. Different elements of time and cost were introduced and their relation to cutting speed were determined. The main contribution of their work was to add the cost of “quality” to the objective function, thus modifying existing models to explicitly recognize how roughness of the part will affect its machining cost. This modification is applicable to those cases where a marginal improvement in the quality of the part may result in the elimination of a secondary process or the use of a different, more costly process [45]. *Somló, J.* [33] used a method, which made possible to enforce the management goals when choosing the cutting parameters. It is possible to solve this problem by the development of the so-called secondary optimization method. The secondary optimization connects the cutting data with the management requirement. The application of this is not trivial because it needs at every new management situation a new technological processing. It is possible to realize the secondary optimization when the machine tool is equipped with adaptive control unit. For this, a new override method was proposed which can also be used in systems without feedback from the cutting process (without AC in the classical sense) using properly suited CNC devices.

3.3.2. A new optimization method based upon intensity type compact variables

This is a new optimization method has been developed by *Tóth, Tibor, Detzky, Ivan* and *Rayegani, Farzad* [36, 31, 44].

The suggested mathematical model is of *three* components are as follows:

(1) Constraints system;

(2) Objective function;

(3) Tool life equation.

The *independent variables (constraint system)* of the model are the parameters to be optimized (e.g. for *turning*: depth of cut (d), feed rate (f) and cutting speed (v); for *grinding* with longitudinal feed: depth of cut (d), longitudinal feed (f) and the revolution number of work piece (n_w)). The *objective function* may be defined as minimum cost or maximum productivity for the given operation element and the *tool life (T) equation* which is the third component of the new model. At this model it is supposed that a proper solution for the model exists and it is a closed set (e.g. variables *(d), (f), (v)* have finite values only).

3.3.3. The advantages and perspective of the new method

Determination of the optimal cutting parameters is especially actual at three different levels of hierarchy in manufacturing engineering:

- At the level of technological process planning;
- At the level of programming the production of flexible manufacturing cells (FMC) and manufacturing systems (FMSs);
- At the level of production process control, including the adaptive control (AC) too.

The results of computer-science and computer technology are increasingly used for performing the optimization at all the three levels, but the used algorithms and their databases strongly differ from each other at each level. At the level of process control the objective function and the constraint-conditions are preliminary fixed and very short time (about 20-80 milliseconds) is available for calculating the optimum parameters. Here the speed of algorithm used for optimization has a great significance. Till now one of the main difficulties of using the Adaptive Control Optimization (ACO) is the strongly limited calculation speed. As a consequence of the changing purpose of production it is typical to use alternate objective functions on the level of manufacturing cells / manufacturing systems. As a general use, the purpose is to reach the minimum cost, but it can be replaced by the minimum machining time, if e.g. it is demanded by the optimization of the erection process being on a higher level in the hierarchy of the full manufacturing process. At the same time it can also occur, that it becomes necessary to increase the tool edge life - i.e. to use less intensive cutting parameters as a consequence of tool-lack. At the same time the basic precondition of actualizing the fine program of production is the determining of optimum cutting parameters. The algorithm used for this purpose shall be quite fast and the used database cannot have a too large size. The optimization program runs in the cell-control (or manufacturing system control) in the background. About 20-70 seconds is available for running the program. The largest database and the longest time are available on the level of technological process planning, and the computer-capacity is also the greatest in this case. As a consequence, the greatest possibility of choosing the optimizing algorithm is ensured in such circumstances. The offered new procedure can be used on all the three levels, of course involving them into frame-programs of different capacity and service-level. It is very perspective in the technological pre-planning too, as a method serving for making of quasi-optimal solutions quickly in a great mass. Namely here the intensity of stock removal *(Q)* can be used suitably for global but relatively exact calculations. Products are complex structured objects, the manufacturing processes of which are decomposed into part manufacturing and assembling processes. In discrete manufacturing technology processes, numerous operations are executed either consequently or simultaneously, in sophisticated interrelationships with one another. Effectiveness of the processes are measured and/or evaluated by means of several complex objective functions (cost, quantity, quality, deadline, etc.) the optimum of which are restricted by complex resource-describing function [31].

3.4. The knowledge-representation methodsin CAPP

Process planning is defined as the act of preparing detailed processing information for the manufacture of a component or an assembly. The content of the process-planning task will differ dependent on the manufacturing environment considered.

Differences in process planning tasks depend on:

- ***The complexity of the product***

On different product-aggregation levels different process planning tasks can be identified, e.g. developing the bill of materials, generating process routings, indicating process specifications.

- ***The level of detail of the process plans***

For instance, in typical conventional machining environments (e.g. tool rooms), no formal process plans are made at all, while the generation of part programs for NC machine tools requires process planning to the highest level of detail. In high volume production the process planning tasks includes the design of the manufacturing system. In small batch part manufacturing the general purpose manufacturing equipment is an important constraint.

Process planning typically deals with the problem of how to manufacture an individual product, being an assembly or a single-part. It aims at manufacturing the considered product in the most cost-effective (economical) way considering technological constraints and preferences. This characterization of process planning, referring to the isolated consideration of the ways to manufacture a single product type, is the most important one for the distinction between process and production planning functions.

In the context of small batch part manufacturing, process planning refers to the task of generating a plan for transforming raw material to its finished form according to design specifications. It deals with the following problems:

- Interpretation of the product model;
- Selection of machine tools;
- Selection of tool sets;
- Determination of set-ups;
- Design of fixtures;
- Selection of machining methods;
- Selection of cutting tools;
- Determination of machining sequences;
- Calculation of tool paths;
- Calculation of cutting conditions;
- Generation of NC -programs.

The performance of the latter six activities mentioned above is often also referred to as operations planning. Sometimes capacity planning is considered a process planning activity. However process planning deals with individual products and is therefore not capable of considering the competition of different orders for the available capacity, the latter being a production planning task. Process planning decisions have always been the domain of experienced planners. Although the experience of the process planner is critical to the success (quality) of the plan, *knowledge* plays an important role too.

Knowledge is accumulation of experience. As such, knowledge comes from own experience or is passed on and is based on the experience of others. Experience is often obtained from earlier training as operator and enriched with knowledge obtained from books, training and discussions with colleagues. To automate process planning it is necessary to store and represent the available knowledge and experience in such a way that it can be used for process planning decisions. There are some types of automated process planning systems (e.g. the variant method, the generative method, the vario-generative method and the expert systems for CAPP).

3.4.1. The variant method

In manufacturing industries the product range is not completely random but can be divided into groups or families of products that are to a certain extent similar. The variant approach to process planning attempts to use this similarity of products in order to reduce the required process planning effort for new products. This approach is based on the assumption that common manufacturing methods can be identified for similar products.

Families are identified by classification of the products based on similarity of certain characteristics. For each of the families a standard template process plan, in which the manufacturing methods are represented, is developed or available. Process planning for a new product includes the classification of the given product; search for the family it belongs to by matching the classification code of the product with the family codes followed by retrieval and extraction of the corresponding template process plan. This process plan usually needs to be modified to satisfythe specific needs of the considered product.

The computer can be used for classification code generation and matching as well as for editing and generation of planning documents. Especially the modification of plans requires extensive human interaction from expert process planners.

This has the disadvantageous that the quality of the eventual process plans still depends on the knowledge background of the process planner, that it can not be used in a fully automated environment and that optimization is not possible. However, the relatively low degree of complexity and corresponding low investment involved in hard- and software makes that the variant approach is still popular [4].

3.4.2. The generative method

In the generative method the manufacturing knowledge is incorporated in the process planning system. The product and manufacturing system information is required as input for the process planning system which generates a new process plan from scratch, with minimum human intervention.

The manufacturing knowledge can be represented in different ways using algorithms, formulas, decision tables, etc. AI techniques, representing another way to record procedural knowledge, are very useful to improve the flexibility and adaptability of generative CAPP systems. Generative process planning systems are more complex than variant type of system. Not only the implementation of decision procedures itself, but even more important, the acquisition of knowledge is very problematic. Moreover, generative process-planning systems are the only adequate method to implement the CIM concept in small batch part manufacturing and despite the problems identified above, generative process planning systems are become available [4].

3.4.3. The vario-generative method

There is also a successful combination of the variant method and generative method so called *vario-generative* method introduced by *Horváth, M.* [20]. He analyzed the advantageous and disadvantageous properties of the variant and generative methods and extracted the advantageous properties, both from the variant and generative methods. He decomposed the database and the program logic and declared neither of them can give specific information. While CAPP systems are moving more and more towards being generative, a pure generative system that can produce a complete process plan from part classification and other design data is a goal of the future. This type of purely generative system will involve the use of artificial intelligence type capabilities to produce process plans as well as be fully integrated in a CIM environment which is called dynamic, generative CAPP system which would consider plant and machine capacities, tooling availability, work center and equipment loads and equipment status in developing process plans. The process plan developed with a CAPP system at this stage (dynamic-generative CAPP system) would vary overtime depending on the resources and workload in the factory. For example if a primary work center for an operation is overloaded, the generative planning process would evaluated work to be released involving that work center, alternate processes and the related routings. The decision rules would results in process plans that would reduce the overloading on the primary work center by using an alternate routing that would have the least cost impact. Finally, this stage of CAPP would directly feed shop floor equipment controllers [27].

3.4.4. Expert systems for CAPP

An expert system is a rule-driven system, which seeks to emulate the reasoning capacity of an expert in a particular area. It has considerable advantaged over conventional structured computer programmers in applications such as process planning for number of reasons. For example, an expert system offers a modular architecture for building large programs, and knowledge in the form of production rules may be added, deleted or modified in the knowledge base without any alteration in the control structure. In addition, expert systems acquire knowledge interactively through dialogue with a user and have the ability to explain the line of reasoning used in any particular situation. They can also perform symbol manipulation so CAD data easily handed. If the decisions of a process planner from the moment he/she look s at a design to final completion of the plan can be captured in computer logic, the problem of automating the process planning functions is virtually solved [31].

Top-down optimising in PPS/PPC and CAPP systems

Optimisation, in the most general sense of the word means that in a system such steps are carried out due to which a maximal effect is realised. This statement is valid provided that a criterion related to the effect in question is available.

According to. *Feldbaum A. A.* optimisation can be defined as searching for solutions scientifically established.

Optimisation problems can be resolved into two main components namely the set of allowed solutions (optimisation range) and the objective function in this range. In case of *n*-numbered independent variables the optimisation range is a part of set of *n*-dimensional vectors. The objective function is defined as a mathematical function extremum of which realises the optimum criterion, and is used for evaluating the solutions. The method of solution in case of large scale tasks depends on the structure of the problem. Multiple-level and hierarchical structure is the special and essential feature of production planning & control and scheduling. Considering the complexity of tasks related to each individual level, then a methodological aspect (approach) so called top-down optimisation method can be utilised (Fig.4.3.), [35].

4.1. The fundamentals of optimisation

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

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

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

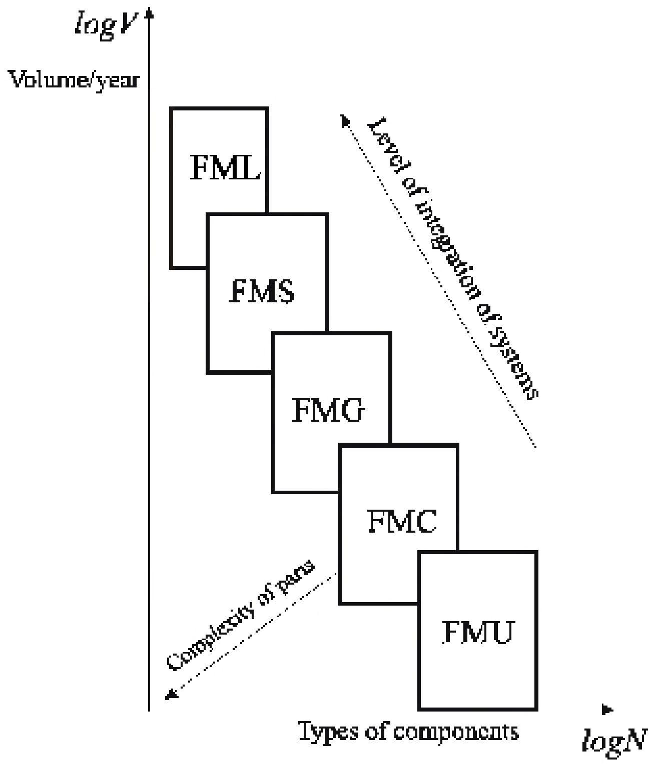
In my Thesis I have used both the two approaches and their combination as well. As general methods belonging to the problem-oriented aspect I utilised the followings:

- The analysis oriented to recognising and knowing the problem;
- The synthesis targeted to solving the problem;

- The optimization suitable for solving the best solutions determined by the given constraint and the valid laws;
- Technical heuristics and modelling and formalization.

As examples to the methodological aspects, the use of *Lagrange multiplier*, and numerical *Newton* methods and computer programming can be mentioned to special problems. Flexible Manufacturing Systems FMSs in general can be regarded as a hierarchical system. In modern FMSs there are so called combined hierarchical and horizontal systems for example a Holonic Manufacturing System HMS [7,46] so on. Hierarchical characteristic of FMSs as an abstract concept is very important considering the optimisation approach.

However FMSs theory is classified into two approaches so called external and internal approaches, and there are fundamentals for external and internal approaches. If we consider the external approach in this case we have to devote ourselves to the subjective properties of FMSs. Considering the external approach it is to classify the flexible manufacturing system into 5 levels in general. This classification can be seen in Fig.4.1. In the figure we can see a log-log diagram where the vertical axis belongs to the annual volume/year and horizontal axis to the types of the components.



4.1. The external classification of FMSs [ref. to *Kusiak, A.*] [27]

Remark: In Fig.4.1, FMS means a collective noun for all the systems on the one hand and, a special kind of FMS-group on the other hand.

As regards the internal approach, the FMSs at least require four hierarchical levels as follows:

1. The work piece-tool subsystem level;
2. The technology work place subsystem level (mechanical subsystem level)
3. The machining or processing subsystem level;
4. The manufacturing system level (Fig.4.2.).

Manufacturing system- in this approach- a hierarchical system which consists of machining and processing objects performing manufacturing orders and its attributes are: manufacturing the work pieces, manufacturing resources, operation sequences and objective functions.

Machining subsystems consist of technological resources, material handling, tool supplying and controlling resources. The activity performed by machining subsystem is the operation. The most important attributes in connection with machining subsystem are: workpieces, operations, tool groups, and objective functions which featuring the function of the subsystem.

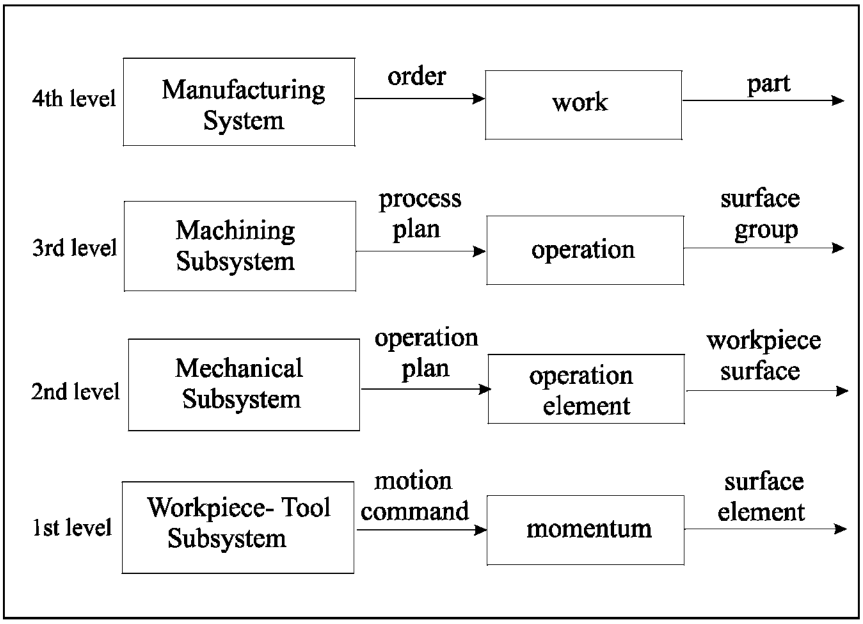


Fig.4.2.Internal Classification of FMSs [35]

A machine tool is the typical *mechanical subsystem* which carries-out technological operation elements. Its important attributes are: tool, tool path and technological parameter values. The workpiece tool subsystem is the lowest hierarchy level and its attributes are: the geometric features of cutting (e.g. in case of cutting), tool wear, work piece quality etc.

4.1.1. The general principle of optimisation in hierarchical system: top- down optimising

In order to illustrate the general top-down optimisation model, let us consider a system of three-hierarchy level (Fig.4.3.), [35].

The model is completely independent one regardless of any special theme (e.g. it can also be used for optimising scientific, political, technological and technical constructions systems).

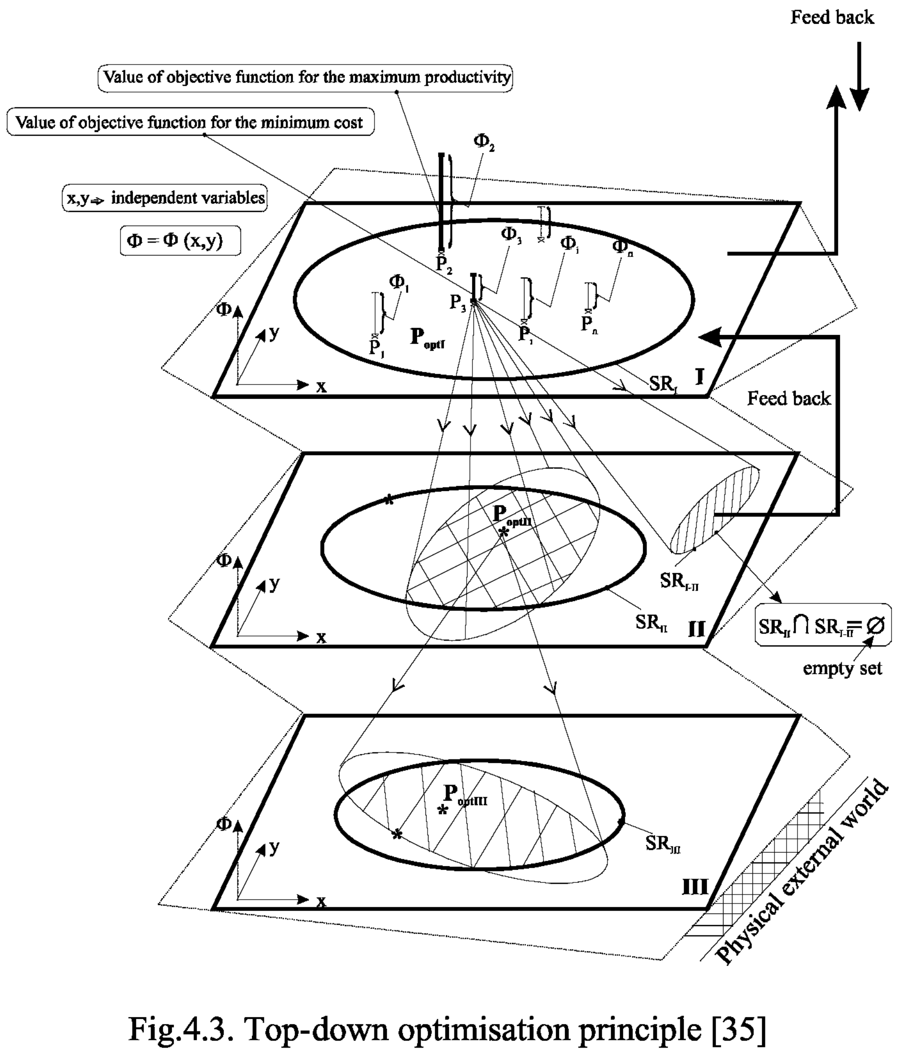


Fig.4.3. Top-down optimisation principle [35]

Considering the top-down and vertical decomposition of the model the first level is the most important one and going down from the top level the importance degree of the other levels are decreasing. Let us consider an optional physical external world. As it was mentioned the highest level of this hierarchy model is the most important one and the degree of importance is decreasing from the first level to the second and from the second level to the third one. To interpret the model we suppose that at the first level we have an optimisation area I (e.g. a plane), we have an independent co-ordinate system (x,y,) and parallel to the z-axis in space there exists a function ϕ. It is obvious that we can only consider $\phi = \phi$ *(x,y,)* and we may call it as a very simple and acceptable co-ordinate system with one function namely ϕ and two independent variables x and y. Of course when there exist two independent variables, only it is possible to show a demonstrative figure where $\phi = \phi(x,y)$, which means, ϕ is a dependent function with two independent variables x and y. However, when there are three, or more independent variables, it is impossible to illustrate a figure, that is why to avoid this problem we suppose that there is only two independent variables x and y and a dependent function $\phi = \phi(x,y)$. But it is to remind that there exist the analogous approaches to the functions with more than two or more independent variables, which are not possible to be demonstrated by means of a figure, but by analogous approach. Let us suppose that at the first level there are n different concrete solutions for example in the case of P_1 we have ϕ_1 and this is a numerical value and in the case of P_2 we have ϕ_2 (we suppose that its value is more than ϕ_1) and so on. In Fig.4.3, we can see that there are different functions values ϕ_1, ϕ_2, $\phi_3 \ldots \phi_i \ldots \phi_n$, and for each of them there exist index points like P_1, P_2, $P_3 \ldots P_i \ldots P_n$, and we suppose that there is an optimum criterion to select the best solution. The optimum criterion from this respect is a degree of goodness and it is absolutely subjective, it can be minimum cost, maximum productivity, minimum time or combination of them, etc.

Connection between objective function and optimum criterion

An objective function can be regarded as a mathematical function and on the contrary optimum criteria is not a function, but a subjective verbal which defines the degree of goodness of selected function. For example we may consider the maximum productivity of a system as an optimum criterion and it is absolutely subjective (it was decided and selected independently). An objective function in the broad sense means such a function that extremum of which realises the optimum criterion suggested by the decision makers taking into consideration all the important constraints. In a system it is impossible to eliminate the constraints, because the functionality of a system is determined by means of constraints, and in optimisation we always would like to search for the best solution fulfilling all the constraints. Considering Fig.4.3., in case of index P_2 the value of objective function is ϕ_2 and the optimisation domain or boundary is SR_I and this boundary has been determined by constraints. Depending on optimum criterion, which is fixed previously, we look for the objective function in the given domain determined by the constraints. The criterion may differ depending on the decision makers. The criterion may be minimum cost, a minimum time, maximum productivity so on, but all of them should be optimised inside the given boundary without elimination of the constraints. For example in the case of maximum productivity criterion, the objective function is the productivity function, in the case of minimum cost criterion, the objective function is the cost function and in the case of minimum time criterion, the objective function is the time function, etc. Why? Because the extremum of the cost function, the productivity function and the time function on the allowed boundary will give the best solutions and this is the absolutely correct connection between the optimum criterion and the objective function suggested or allowed by the constraints. Continuing with the principles of optimisation we would like to allocate to this general hierarchy model (Fig.4.3.), a special internal hierarchy approach related to flexible manufacturing system (e.g. manufacturing system, manufacturing cell, machine system , mechanical system and work piece- tool system) and we suppose that our objective function is the cost function and the minimum value suggested by the decision makers is the minimum cost. We indicate P_3 as an optimum point. If there is a potential optimisation area SR_{II} at the 2^{nd} level II, then this question arises- what is the connection between 1^{st} and 2^{nd} levels ?- We know that at the second level II, the potential optimised area SR_{II} has been suggested based on the constraints existing at the second level II, then if the 1^{st} level I transforms some additional constraints to the second level II (this transformation was illustrated by means of conical projection from the given point in SR_I in the first level I to the second level II) in a lucky situation we will obtain a common area belonging to the both boundaries SR_I and SR_{II} and this common area is the allowable potential optimisation area suggested by the first level I and second level II. But all the time we are not lucky and there is no a common area. For example we can imagine the suggested area by the first level I is SR_I and the suggested allowable potential area by the second level II is $SR_{I\text{-}II}$, then as is shown in Fig.4.3, we can not find any common area between two areas. In this case using the mathematical equation, we can define the following: $SR_{II} \cap SR_{II-I} = \varnothing$, which means that, the intersection of two selected or suggested boundaries related to the first and second levels I and II is disjunctive or in other word this is an empty set. Then what is to be done ? There are two possibilities. First we try to feed back to the first level and use all the optimum points in the given boundary and project them to the second level. If we are lucky then there should be some common areas between the suggested potential areas, if not the second possibility is to feed back to the upper levels and look for the optimum points at the suggested boundary. Then in the upper level there will be a new suggestion, and considering all the other constraints a new optimisation boundary will be suggested which will be accepted at the other levels as well. Of course there may be several times of feed backing, but the solution will be obtained. Following the procedure if at the third level there has been suggested a potential optimisation area SR_{III} and there is no any empty set between two areas SR_{II} and SR_{III} (in lucky case), then the result is the solution, if not then the procedure should be continued by means of feed backing till the best solution to be obtained. This method is completely new and general and it is not only used in technological field but in other fields as well. This is a HUNGARIAN approach and very powerful method to be used in any field. In this approach we have to take into consideration that the “bottom-top” optimisation is impossible as it was mentioned the degree of the levels is increasing from bottom to top and vice versa. It means that the level III is less important than the level II and the level II is less important than level I.

4.2. Top-down optimizing in PPS/PPC system

TABLE 4.1
Top-down optimising in PPS/PPC

Optimisation Level	Conditional (Constraints) Systems	Optimum Criterion (verbal form)
Production Planning (1-3 months)	Technology Facilities Personal Resources	**WHAT ?**
Production Scheduling (5-10 workdays)	Technology Facilities Personal Resources **WHAT**	**WHERE ?**
Production Programming (8-24 hours, 1,2,3 shifts)	Technology Facilities Personal Resources **WHERE**	**WHEN ?**

Preliminary Activities

PPS/PPC

Event Driven,
On- Line,
Real Time Activities
(CAM, CAST)

Time-horizon based decomposition

In order to describe the “top-down” optimization procedure in PPS/PPC system, let us consider table 4.1 which was developed absolutely in a general form, we will use the verbal approach (optimum criterion) without any mathematics, but only the logical approach, we suppose that in the first column we have the optimization levels, in the second column the conditional (constraints) systems and in the third column the optimum criterion (in textual or verbal form).

4.2.1. Adopting the general top-down method to PPS/PPC systems according to time horizon

Let us suppose that there exist three time horizons (the time-horizon based decomposition). We determine one- three months for production planning, five-ten weekdays for production scheduling and eight- twenty four hours (1,2,3 shifts) for production programming and we can call them "Preliminary Activities" (actions). Let's imagine there is a boundary line and opposite to the "Preliminary Activities" direction we have so called Event Driven, On- Line, and Real time activities (actions) which are Computer-Aided Manufacturing (CAM) , Computer-Aided Storage and Transportation (CAST), and other similar activities, etc. Considering the second column (the constraints) in Table 4.1, we have the followings:

- Technology;
- Facilities;
- Personal Resources.

Now at this point where the optimisation levels and the constraints are known, this question arises: what should be planned ? What kind of components or products should be manufactured? This is an optimum criteria or a new condition after decision making from scheduling point of view. Then it is impossible to change the component parts and series of components. This is fixed here and what is the new optimum criteria at the second level? This is a new part of condition system. The elements of the constraints (conditional) system at the second level are absolutely the same but there is an additional complimentary new condition namely (what). What kind of products will be produced with in this time internal in the workshop and the new suggested optimum criteria at the second level is (where). It means that: where is the workplace, for producing the previously fixed and determined product. And this is a special technical resource (maybe a machine tool, machining system, machine cell, the heat treatment workplace or a manual workplace. This is an optimum criterion where together with the workers/experts are capable to carry on the suitable operation (operation element or operation element group) of some kind of heat treatment, or may be some kind of measuring using instrument so on. The second optimum criteria at the second level is (where)- if you consider Johnson's algorithm- we have given product or work piece series. From scheduling point of view where means: Which one will be the first at the first machine tool? Which one will be the second at the first machine tool? Which one will be the i-th or j-th at the second machine tool. And it also means where will the components part be produced? If you consider what and where as the new conditions at the first and second levels, then it is obvious that the new optimum criteria is (when), and it is absolutely logical, there is one to one correspondence.

We have three hierarchy levels in this concrete production planning scheduling and programming case, we have also three hierarchy levels in the general mathematical and general model and Table 4.1 is absolutely correct for production planning and scheduling. As a general tool for FMSs decomposition, let us consider the internal approach of Flexible Manufacturing

Systems (Fig.4.4.). First we consider two important levels in manufacturing systems, namely social levels and material science levels. The upper boundary levels (social levels) are:

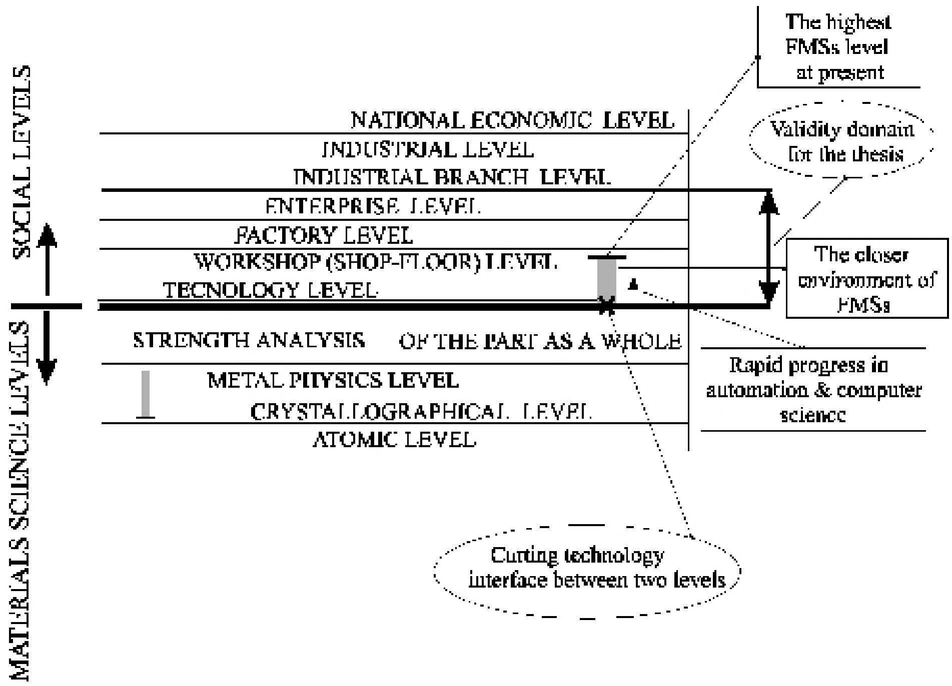


Fig.4.4. Social and material science levels

- Technological level;
- Workshop (shop-floor) level;
- Factory level;
- Enterprise level;
- Industrial branch level;
- Industry level ;
- National economic level;
- International level.

Considering the motivation of the author's dissertation it will be enough to consider the first four levels (technology level, workshop level, factory level and enterprise level). It means that, based on the given technology profile (e.g. cutting technology, metal forming technology, welding technology, and ultrasonic technology, so on) what levels must be optimised. It is clear that technology level due to rapid progress of automation and computer science is increasing and there is no doubt that in the recent years it has been already impossible to follow the modern technology. This gives the possibilities to create better controlling equipment, better organising, and better machine tools etc. But considering the flexible manufacturing systems we can admit the fact that it is somewhere at the highest point of the technology level, taking into account the Artificial Intelligent (AI), computerised robotics systems and

PLC, etc. The material science levels are the characteristics and properties of the materials which are taken into consideration for producing a part. For example in cutting technology there are interrelationships between materials from the material science levels and tools from the social levels. In this respect the material surface from the lower level and the technology from the upper level has been taken into consideration.

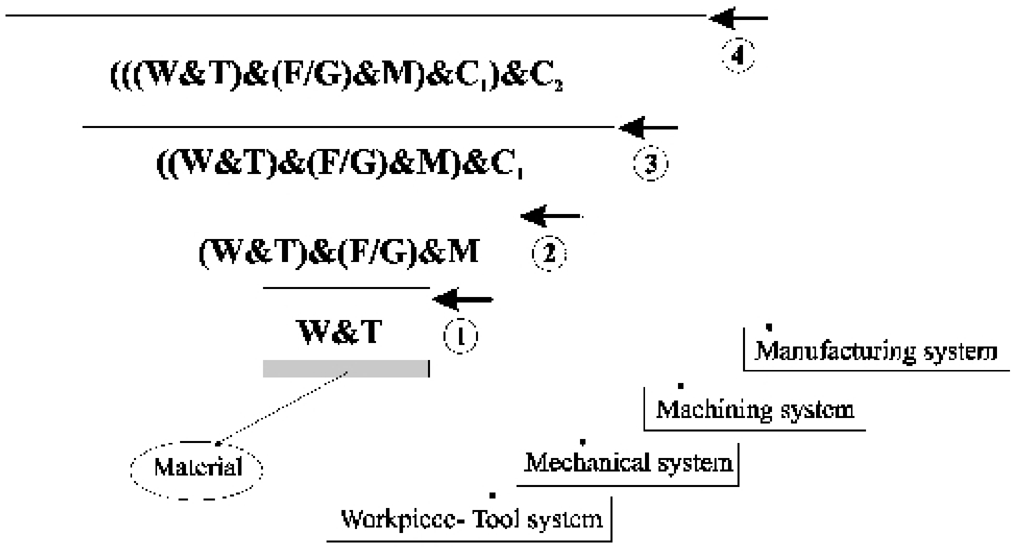


Fig.4.5. Decomposition of FMSs according to internal hierarchy

How ever there are very simple tools and complicated work pieces and vice versa. But it is not important how simple or complicated the tool is or vice versa. The most important thing is -there is an interrelationship between work piece and tool independently from the complexity or simplicity of whether work piece or tool. Following the internal approach of Flexible Manufacturing Systems FMSs. We define the followings (Fig.4.5.):

1. We have the work piece (W) and the tool (T) and somewhere between the social levels and the material science levels (Fig.4.9.) there is a special interrelationship (e.g. primary and secondary processes) and according to the hierarchy characteristics of the system, it is the first level in the internal structure of FMSs.

2. At the second level we have (W&T) & fixture and jig (F/G) & machine (M) and this is a real subset of the system as a whole.

3. At the third level we have ((W&T) & (F/G) & M) and we suppose that we have some kind of control system denoted by C_1.

4. At the fourth and the last level we have (((W&T) & (F/G) & MT & C_1) & C_2. And C_2 is the new control system.

Tool life synchronization in case of a prescribed average tool life

Nomenclature:

C_v	: lst Taylor constant
D_i	: diameters of chain elements [mm]
d_i	: depth of cut for the i-th chain element [mm]
f_i	: feed rate for the i-th chain element [mm/rev]
L_i	: length of the i-th chain element [mm]
m	: Taylor constant exponent for tool life
n_i	: spindle speed [rev/mm]
N	: number of cuts
T_w	: weighted average tool life [min]
T_{allow}	: allowed tool life [min]
T_i	: local tool life for the i-th layer [min]
$t_{m,i}$	: machining time for the i-th layer [min]
v_i	: cutting speed for the i-th surface [m/min]
w	: tool wear [µm],
x_v	: 3rd Taylor constant
y_v	: 2nd Taylor constant
z	: number of chain elements

There have been a lot of efforts concerning optimization of cutting conditions. In this respect we may say that technological parameters have the best roles, as they control the economical aspects. The optimum determination of cutting parameters depth of cut *(d_i)*, feed rate, *(f_i)* and cutting speed *(v_i)*) is of a great importance especially for NC/CNC machine tools. Increasing the intensity of these parameters may result in decreasing the machining time of the given operation, but at the same time, it increases the tool cost as a consequence of loading and wearing of the tool, which is not economical and cost effective. Then we can realize the fact that there will be contrasted effects if we do not select appropriate cutting parameters. In order to find a reasonable compromise it is necessary to solve optimization problems. This part of the Thesis aims at *optimization of tool life* using appropriate cutting parameters. The results obtained from this trial are decrease in feed rate, decrease in spindle speed and arrangement of surfaces of workpiece to be machined in accordance with decreasing machining times, which in consequence is increasing the tool life. Solution of this optimization problem needs determination of machining time, determination of weighted average tool life taking into consideration the local tool lives for number of cuts, arranging the surfaces in accordance with decreasing machining times and database using computer program. Let us assume that a general rough turning process will be performed and dimension chain of a shaft (see: Fig.5.1.) has been given in accordance with the machining sequences (removal of stock): D_i , L_i, (i=1,2…z). In addition to this, the cutting parameters along with allowable tool life are known. The workpiece is machined without changing the tip edge. The explanation for the process is as follows (Fig.5.2.): The given tool edge is used under changeable cutting conditions. For the sake of simplicity we suppose that the edge is used according to the first $w = w(t_m)$ curve until the machining time $t_{m,1}$ (see curve 1, point A). From this point because of the higher cutting intensity we change the cutting conditions, then the tool wear will follow curve 2 (see phase A→ B, until the machining time $t_{m,2}$).

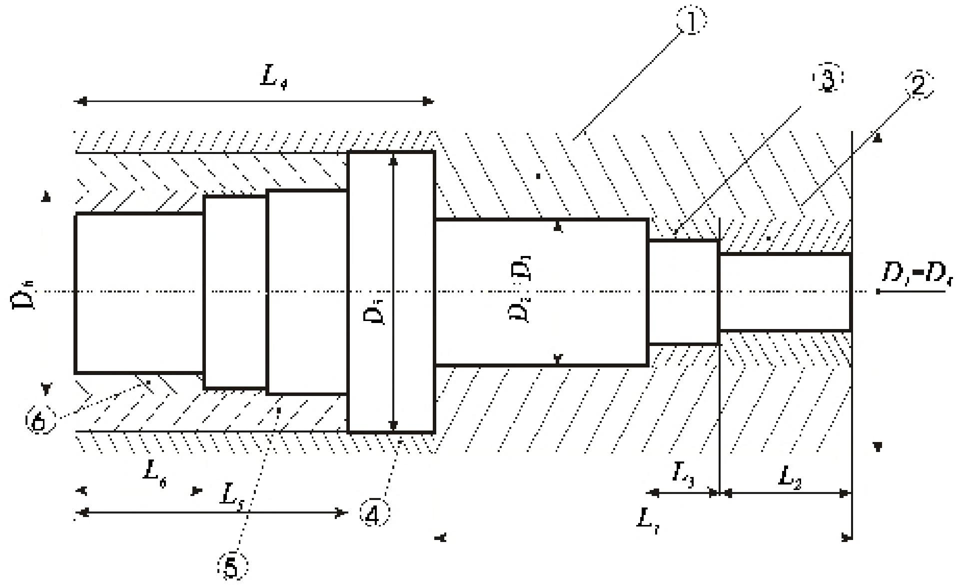


Fig.1. 5.1. An example of workpiece to be cut

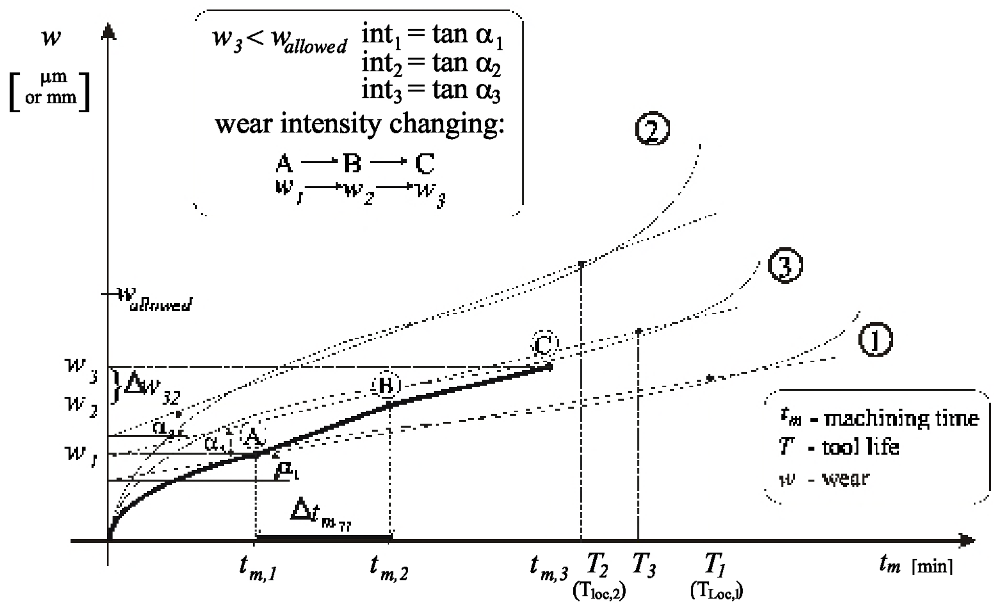
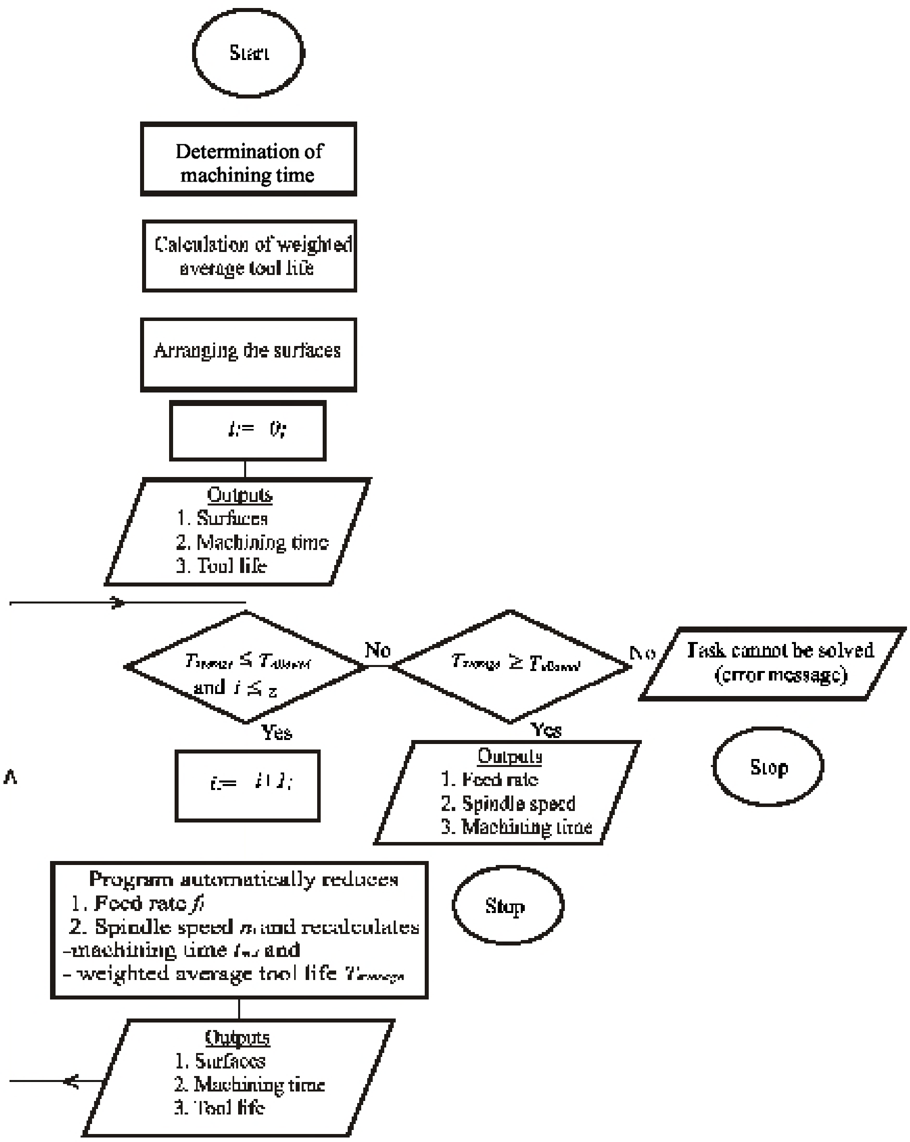


Fig.5.2. Relationships between machining time and tool wear

At the machining time $t_{m,\ 2}$ we also change cutting conditions according to curve 3 until the machining time $t_{m,\ 3}$. Here the wear intensity are denoted by $int_1 = \tan\alpha_1$, $int_2 = \tan\alpha_2$ and $int_3 = \tan\alpha_3$ where the smallest is $int_3 = \tan\alpha_3$ in this theoretical relationships. Then our suggestion is to calculate a weighted average tool life T_w (min) with respect to each local tool life T_i (min) in accordance with its proportional weight. It means that if a layer removal is very time consuming, then the local tool life belonging to it will influence the average tool life proportionally to a greater extent in comparison with another layer removal of which needs smaller time [8].

5.1. Elaboration of an algorithm for tool life synchronization



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

5.2. The technological factors and cutting data

Let us consider the following building block for turning operation [23]. The building block illustrates the major factors that effect metal cutting operations on CNC and NC machines. These factors are tool, coolant, workpiece, and material. The actual cutting data or in other word the technological parameters for the given work piece (Fig.5.1.) are: depth of cut, feed rate cutting speed and spindle speed. These parameters are very important, because they fulfill certain quality requirements desired by the customers. From the programming point view regarding this Thesis there are two important technological parameters namely feed rate and spindle speed. As is known feed rate is the tool movement (traverse) in machining direction. The feed rate is determined by the programmer, he inputs the amount of the feed either by workpiece revolution/min or mm/min. Feed rate determines the machining speed. For this reason, the feed rate is generally chosen at a level dictated by the available cutting force and by the required surface finish.

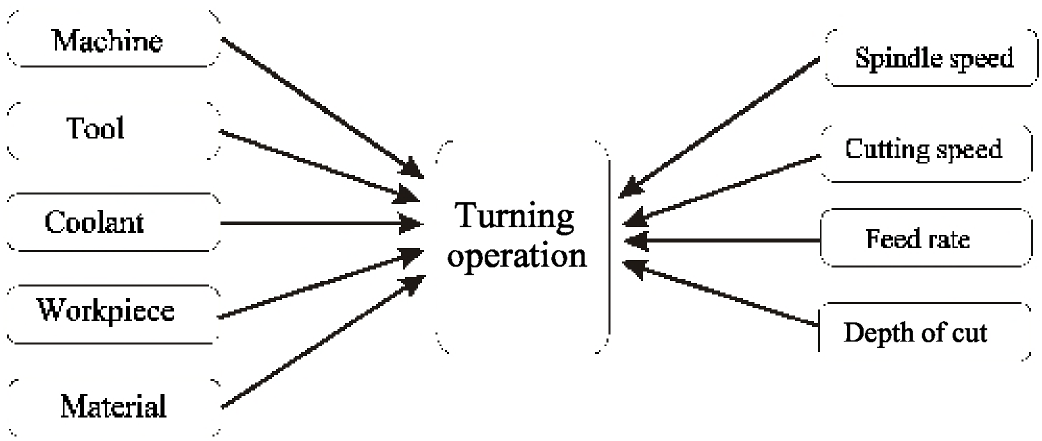


Fig. 5.3. Building block of turning operation in general

Spindle speed is also an input. Actually it is essential to note that the direction of spindle rotation (clockwise or counter- clockwise). In many machining operations it may prove advantageous to restrict the spindle speed within certain limits. For example, in turning operations the pressure acting on chuck jaws may be severely reduced at high speeds because of centrifugal force so that the safe chucking is no longer assured. Then the actual aim is to increase the tool life against wear arranging the surfaces of the work piece in accordance with decreasing machining times. Wear usually occur at the contact faces between workpiece and tool. Excessive mechanical stress brings the risk of tool breakage. Resistance to these stresses (pressure, friction, temperature and chemical conditions) can be achieved by means of employing tool materials or by optimization of tool life.

5.3. Inputs data for elaboration of an algorithm

The important factor that can be controlled by the programmer in connection with cycle time is "stock removal volume" which is usually (cm^3/min). This results from multiplying feed rate by depth of cut and cutting speed; the larger any of these three factors, the greater the stock removal volume per minute. These three important parameters along with geometry of the workpiece, number of the cuts, depth of cuts and spindle speed are the inputs for elaboration of the algorithm to be used for developing a program. (Fig.5.4.).

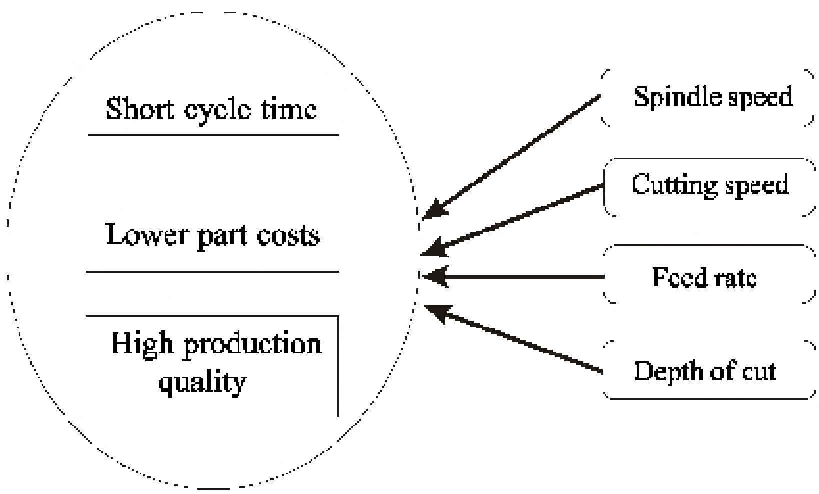


Fig.5.4. The metal cutting data for tuning

It must be noted, however, that high rates of stock removal lead to higher tool wear thereby increasing the average cycle time due to tool or tool tip changes.

Metal cutting data should therefore be chosen so that the wear related tool costs do not exceed a certain level. In this context, it is necessary to consider the use of <u>*optimization of tool life*</u>.

5.4. Determination of machining times

The machining time can be obtained from the following equation [35, 36, 44]:

$$t_{m,i} = \frac{L_i}{f_i.n_i} N \quad \text{[min]}. \tag{5.1}$$

The relationship between spindle speed and cutting speed is given by the following formulae:

$$v_i = \frac{D_i \pi . n_i}{1000} \approx v_i = \frac{D_i . n_i}{318} \quad \text{[m/min]}, \tag{5.2}$$

and

$$n_i = 1000 \frac{v_i}{\pi . D_i} \cong \frac{318 v_i}{D_i} \quad \text{[r.p.m]}. \tag{5.3}$$

5.5. Determination of weighted average tool life

The weighted average tool life is as follows:

$$T_{average} = \frac{\sum_{i=1}^{z} T_i t_{m,i}}{\sum_{i=1}^{z} t_{m,i}} \quad \text{[min]}. \tag{5.4}$$

5.5.1. Calculation of local tool lives

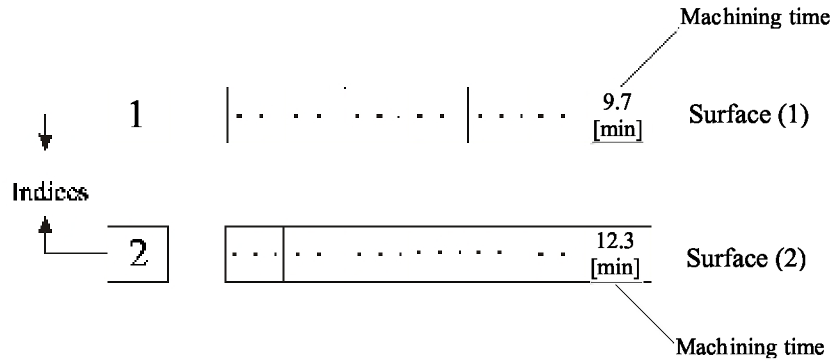
In order to evaluate the local tool lives T_i it is necessary to use the extended *Taylorian* tool life equation as follows:

$$T_i = \left[\frac{C_v}{d_i^{x_v} f_i^{y_v} v_i} \right]^{\frac{1}{m}} \quad \text{[min]}. \tag{5.5}$$

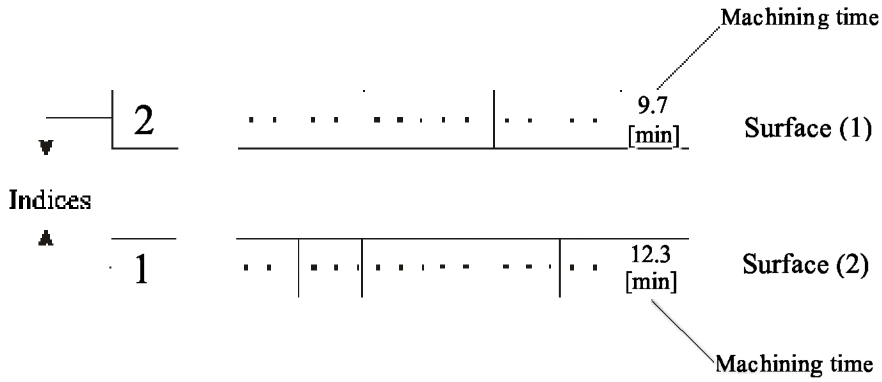
Here C_v, x_v, y_v and m are empirical parameters depending on both the given workpiece to be machined and the tool edge as well. The depth of cut d_i (mm), feed rate f_i (mm/rev) and the cutting speed v_i (m/min) are independent variables, which are based on the machine tool characteristics as well as shop floor control. Applying equations (5.1) and (5.5) the weighted average tool life is obtained and it can be compared with the given allowed tool life.

5.6. The method of arranging (sorting) surfaces in accordance with decreasing machining times

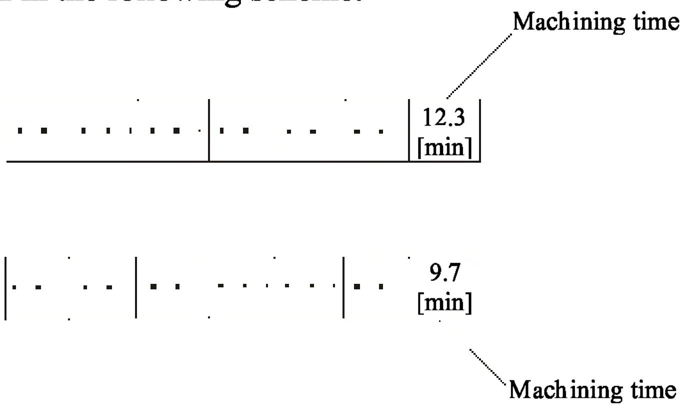
The data for machining the surfaces are stored in arrays and the content of the arrays are feed rate, spindle speed, machining time, geometry of the workpiece and allowed tool life. It is not practical to move (change the order themselves) all the data according to decreasing machining times. Then the best way of solution is to arrange the data by arranging their indices. Then the data are not touched, they occupy the same storage place and we move (change positions) only the indices of them. For example if the data are in records like the next pair of surfaces:



Then after changing the indices, they will be illustrated as follows:



As is shown only the indices were changed and the data (machining times) were stored at their main places *instead of* physical arrangement which is demonstrated in the following scheme:

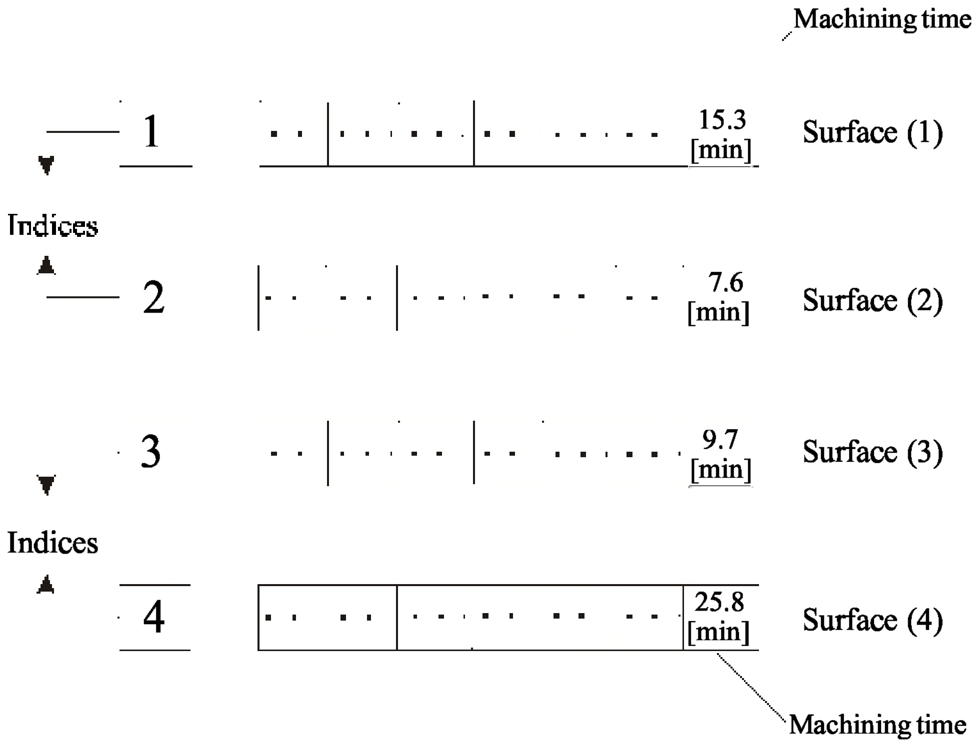


Then it is obvious that changing a couple of indices is much more easier than changing amount of great data organised to be recorded. Here *optimization* is a loop of reduction feed rates and spindle speed while weighted average tool life is smaller than the allowed tool life and number of the steps done not for all surfaces. All results are sent into a temporary file, which can be printed later. If the loop finishes with a higher weighted average tool life than the allowed tool life, then data for surfaces are sent to output, otherwise an error message appears both on the screen and in output file with a content:

Task can not be solved without tool edge changing. Please decrease the intensity of technological parameters or select a more appropriate tool!

5.7. An example of arranging the surfaces based on decreasing machining times

Let us suppose we have only four surfaces with the original relevant data (machining times,) and original indices of surface ordering. As is shown considering the machining data column we can observe that at the fourth surface the machining time is the highest.



The second highest value belongs to the first surface; the third highest value to the third surface and in the end the second surface has got the lowest value of the other four surfaces. Then we will look for the surface with the highest value of machining time and only change its index number with the index number of the first surface.

In our example the suitable ones are surface four and surface one. Then at the first step considering the column of indices at the zero step we change the index of surface one with the index of surface four. Then the order of the indices is changed from order at the zero step into the order at the first step as is shown in Table 5.1. At the second step we do not touch the index four as it is the index with the surface of highest machining time and we look for the other three surfaces with their highest machining times, which in our example this value belongs to the surface one.

Then at the second step considering the column of the indices at the first step we change the index of surface two with the index of surface four. In the end at the third step we consider the column of the indices at the second step and order the changes as is shown in the column of indices at the third step.

Table. 5.1

Machining time	Surfaces	Indices at the 0^{th} step	Indices at the 1^{st} step	Indices at the 2^{nd} step	Indices at the 3^{rd} step	....	Indices at the n^{th} step
15.3 min	S_1	1	4	4	4		
7.6 min	S_2	2	2	1	1		
9.6 min	S_3	3	3	3	3		
25.8 min	S_4	4	1	2	2		
.			.				
.			.				
.			.				
.			.				
n	n	n	n	n	n	n	n

It should be noted that in our example indices of surfaces two and three at the second and third steps remained at their proper places as their machining times have been realized the lowest ones after the fourth and the first surfaces, then if we consider more surfaces it might not be the case, that is why in Table 5.1, we have *n* number of steps, *n* surfaces and *n* machining times. Then considering our example the end result of the ordering through all the three steps will be converted into the following order as is illustrated in Table.5.2.

Table. 5.2.

Machining times	Surfaces	The end result of the ordering of the surface indices
25.8	S_1	4
15.3	S_2	1
9.7	S_3	3
7.6	S_4	2

Table 5.2, shows that index of surface one has been changed with index of surface four, the index of surface two has been changed with the index of

surface four and indices two and three were remained in their proper places (see Table.5.1.).

5.8. The database used for the developed program

All database used for the developed program was collected form the literature [35].

As regards the characteristics of the developed program the user can whether give the inputs data according to its desire or chose from the database actuated in the program itself. The latter is preferable.

The mentioned database can be found in Appendix (1).

5.9. The developed program

The program has been developed under Turbo Pascal (version 7.0).

The program package consists of the following files:

- TOOLLIFE.EXE – Executable program (main program),
- TOOLFORM.TPU- Mathematics which were used in TOOLIFE program (formulae),
- TOOLMISC.TPU- Utility procedures (miscellaneous routines) used in the program,
- TOOLLIFE.PAS – Source codes,
- TOOLLIFE.DAT – Cases for computation (input database),
- TOOLLIFE.TEC – Technical database collected from literature,
- TOOLLIFE.TXT – Case optimization output file results.

<u>**Note**</u>: At the program the spindle speed n_i (rev/min) has been denoted by <u>RPM</u>.

5.10. An example of running program

Let us have a workpiece (see Fig. 5.1.) and apply rough turning process to a with the following data:

- Geometry data are known,
- Technological parameters are known,
- Allowed tool life along with number of cuts and depth of cuts has been given.

It is supposed that the workpiece consists of six chains and of the depth of cuts for each surface is the same. The task is the following:

1. Determination of machining time.
2. Calculation of the local tool lives.
3. Determination of the weighted average tool life.
4. Arranging the surfaces in accordance with decreasing machining times.
5. Optimization of tool life with decreasing the feed rates and spindle speed.

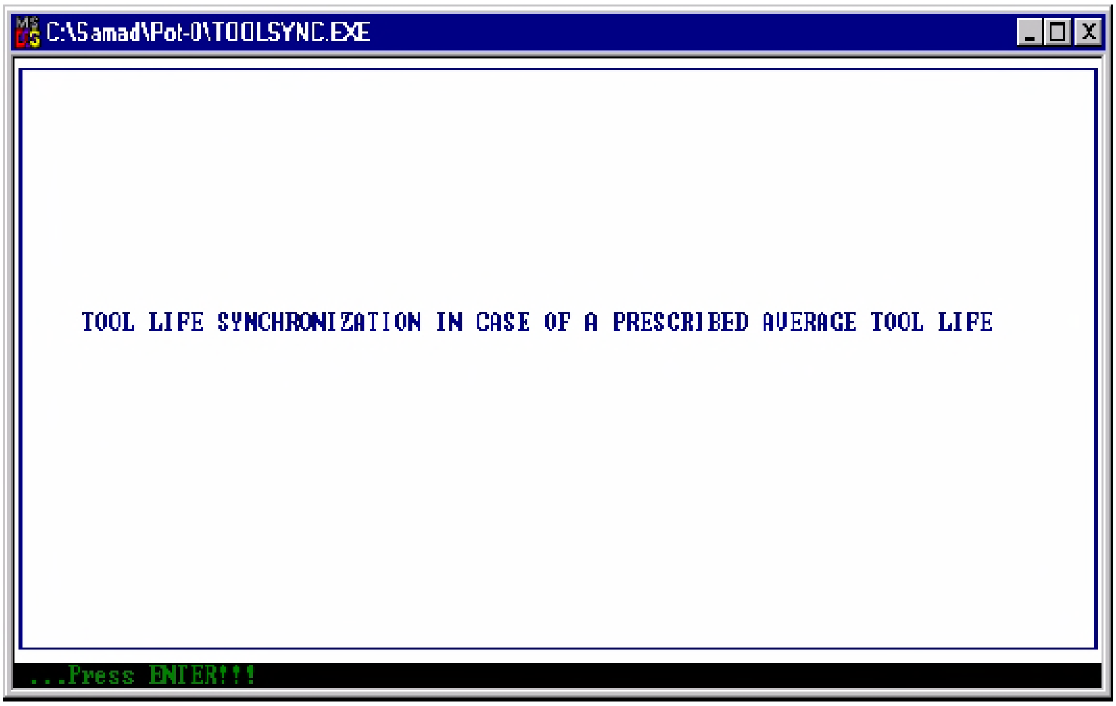


Fig.5.6. An example of EXE. File used for running program

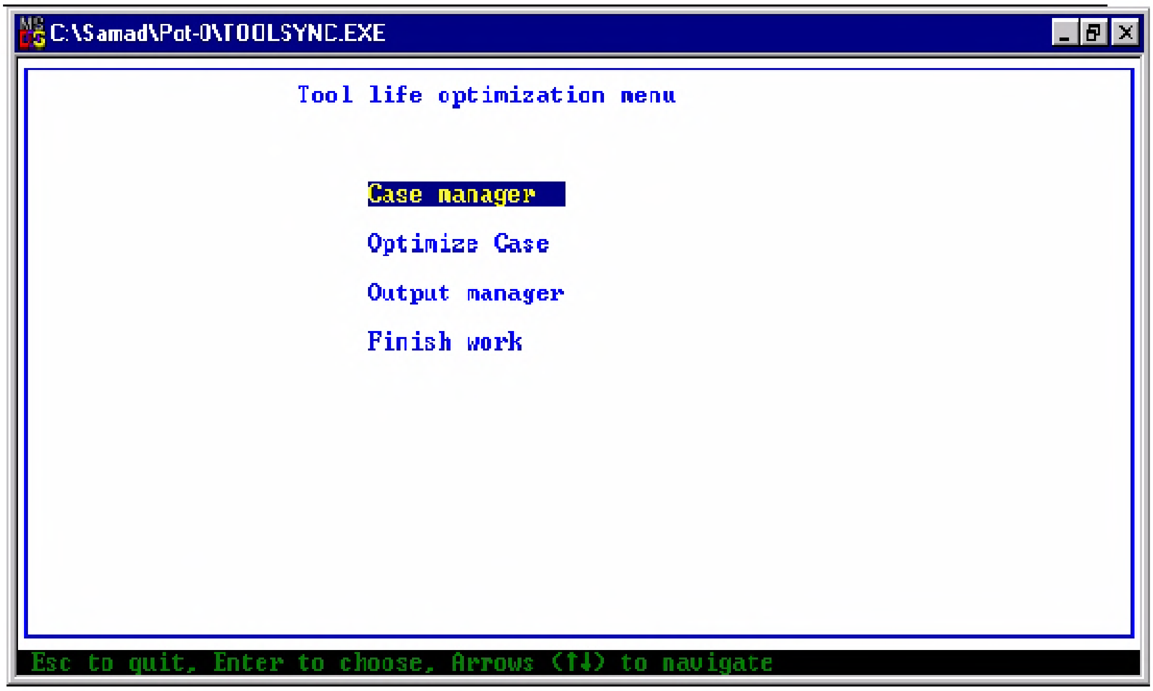


Fig.5.7. Tool life optimization menu

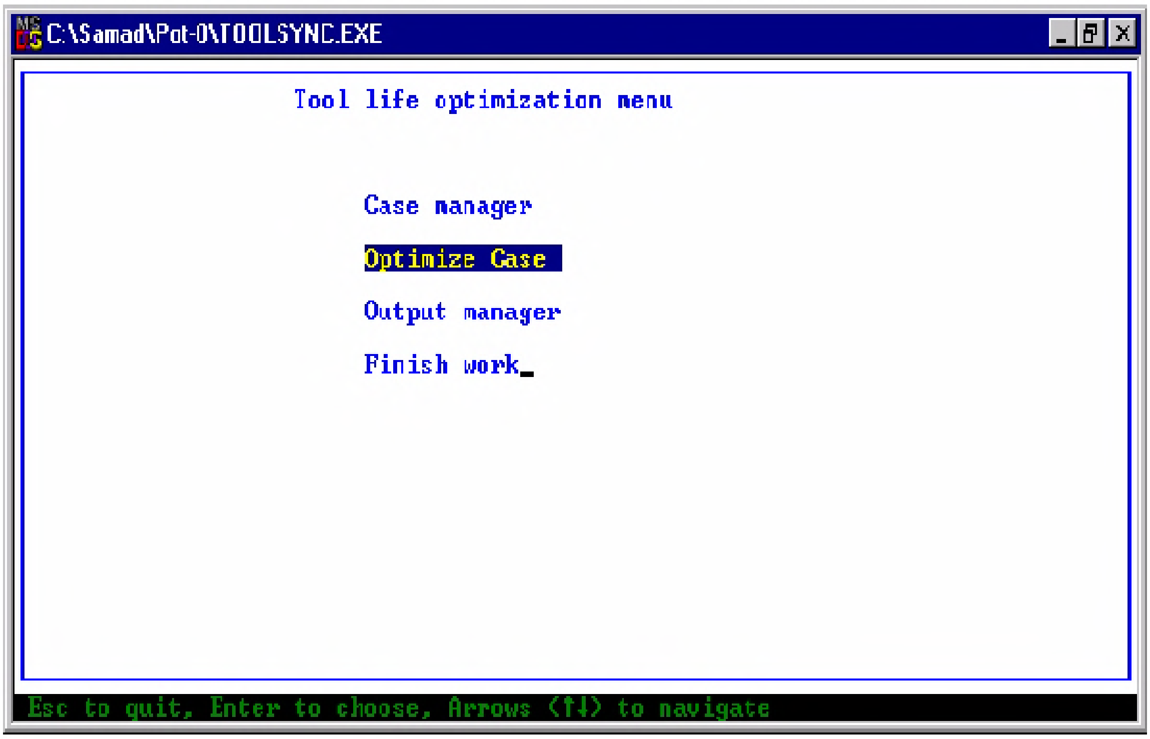


Fig. 5.8. Optimal selection from tool life optimization menu

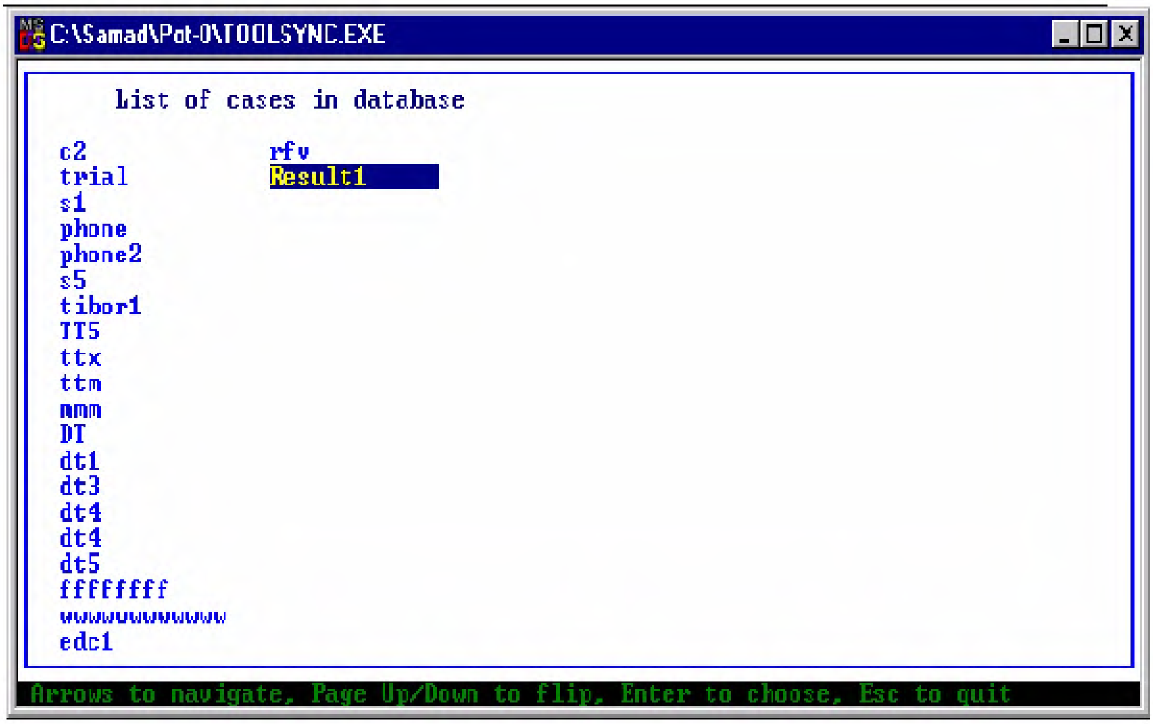


Fig.5.9. An example of database selected from the list of the cases which have already been optimized

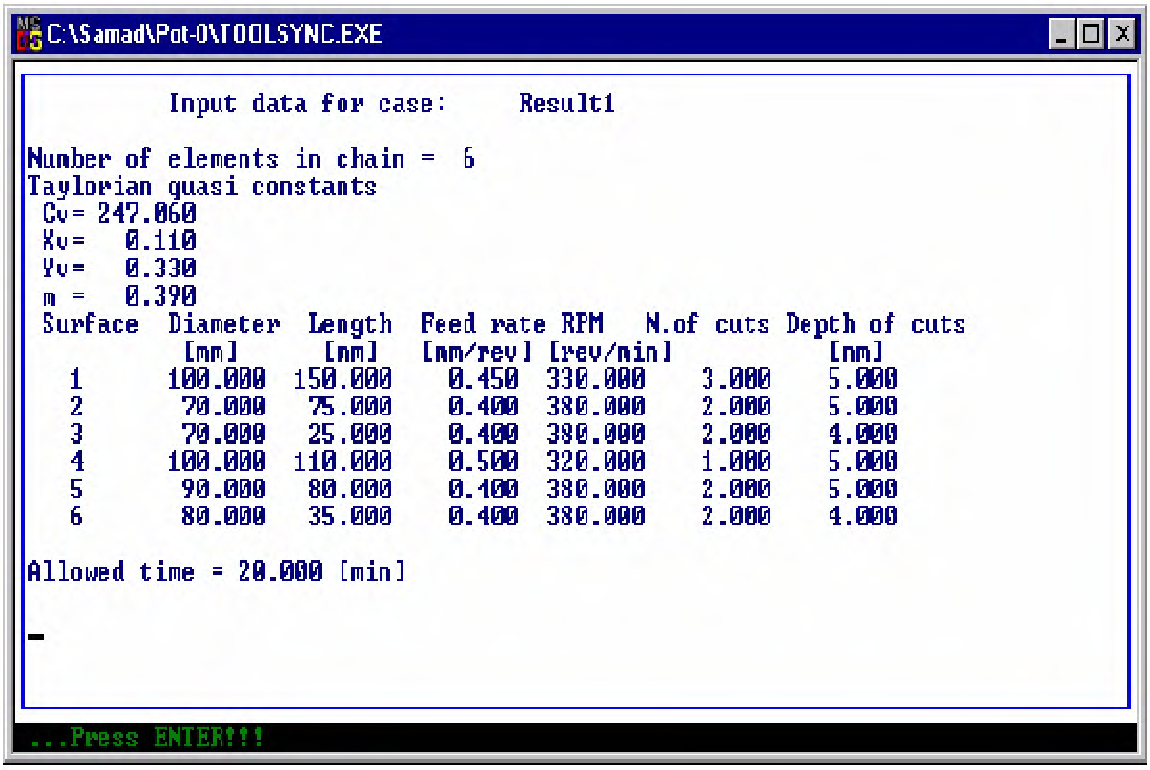


Fig.5.10. An example of input data

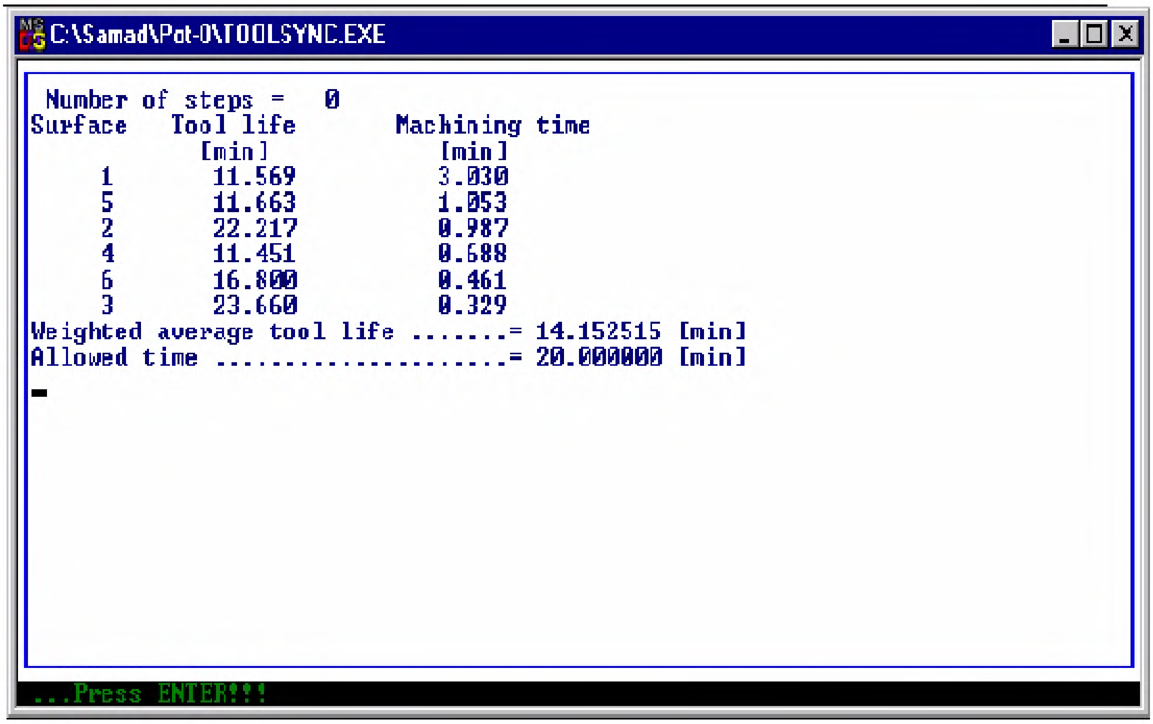


Fig.5.11. Calculation of machining time, weighted average tool life in accordance with arranging surfaces at zero step (without reducing the spindle speed (rev/min) and feed rates (mm/rev))

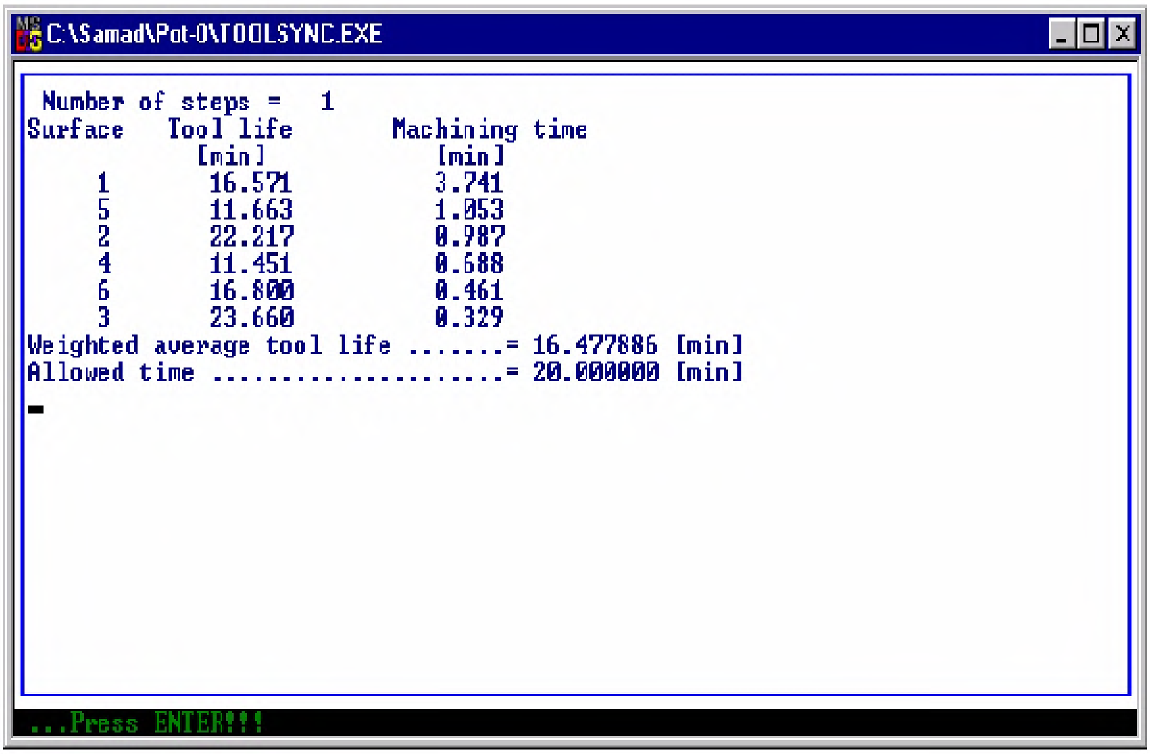


Fig.5.12. The first step of optimization where the average tool life increasing along with increasing the local tool life and machining time at the first step

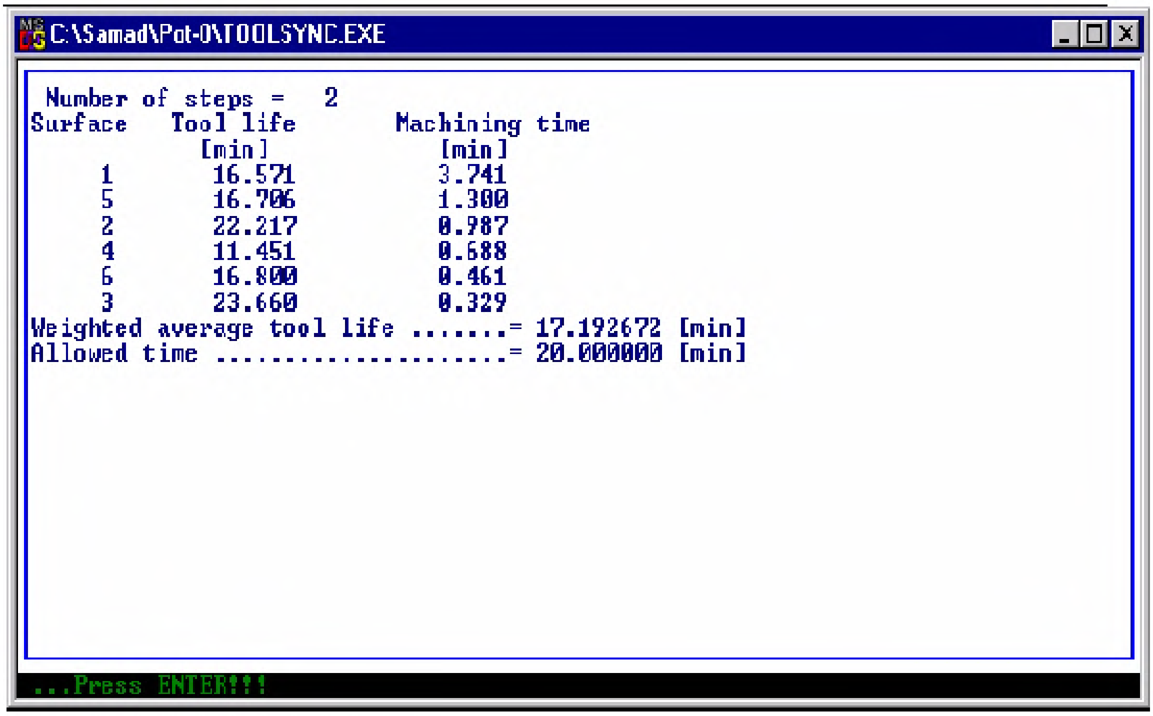


Fig.5.13. The second step of optimization where the average tool life increasing along with increasing the local tool life and machining time at the second step

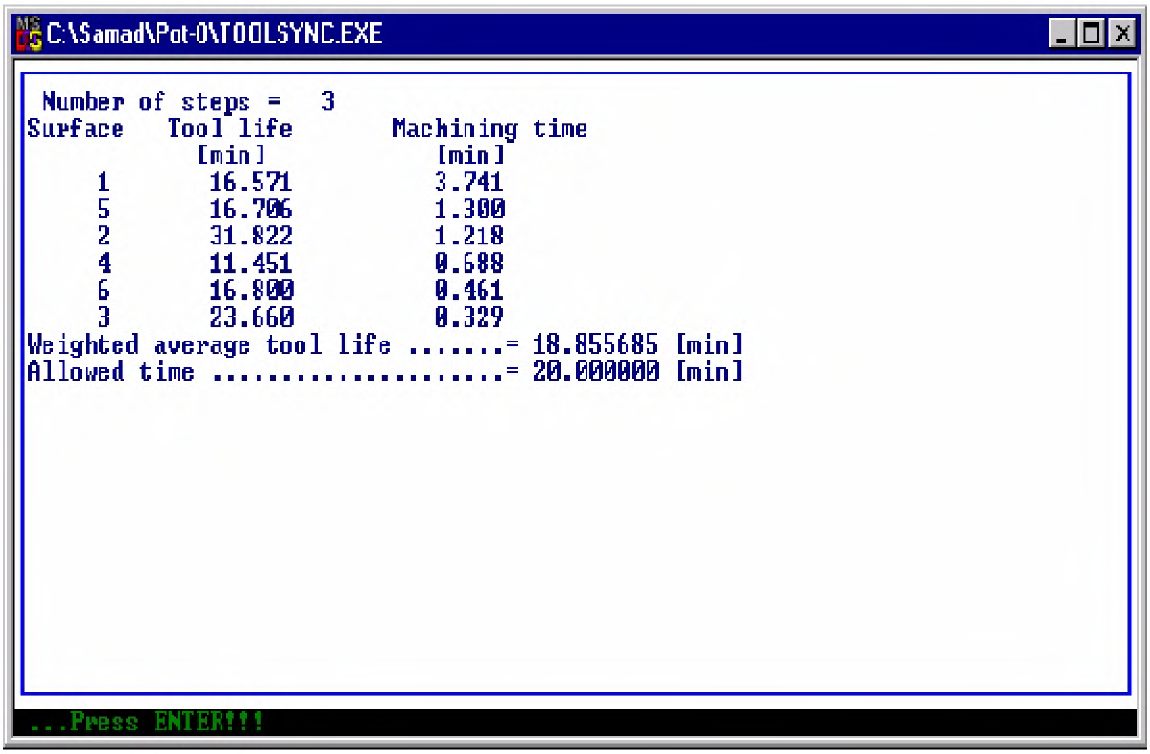


Fig.5.14. The third step of optimization where the average tool life increasing along with increasing the local tool life and machining time at the third step

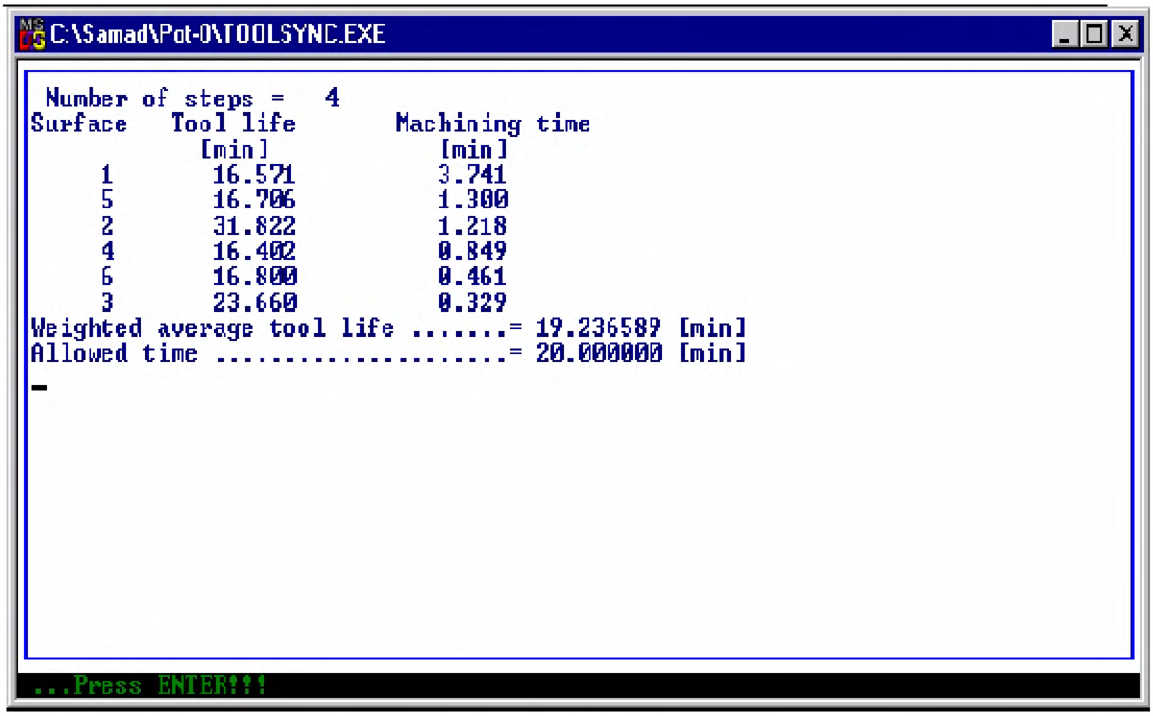


Fig.5.15. The fourth step of optimization where the average tool life increasing along with increasing the local tool life and machining time at the fourth step

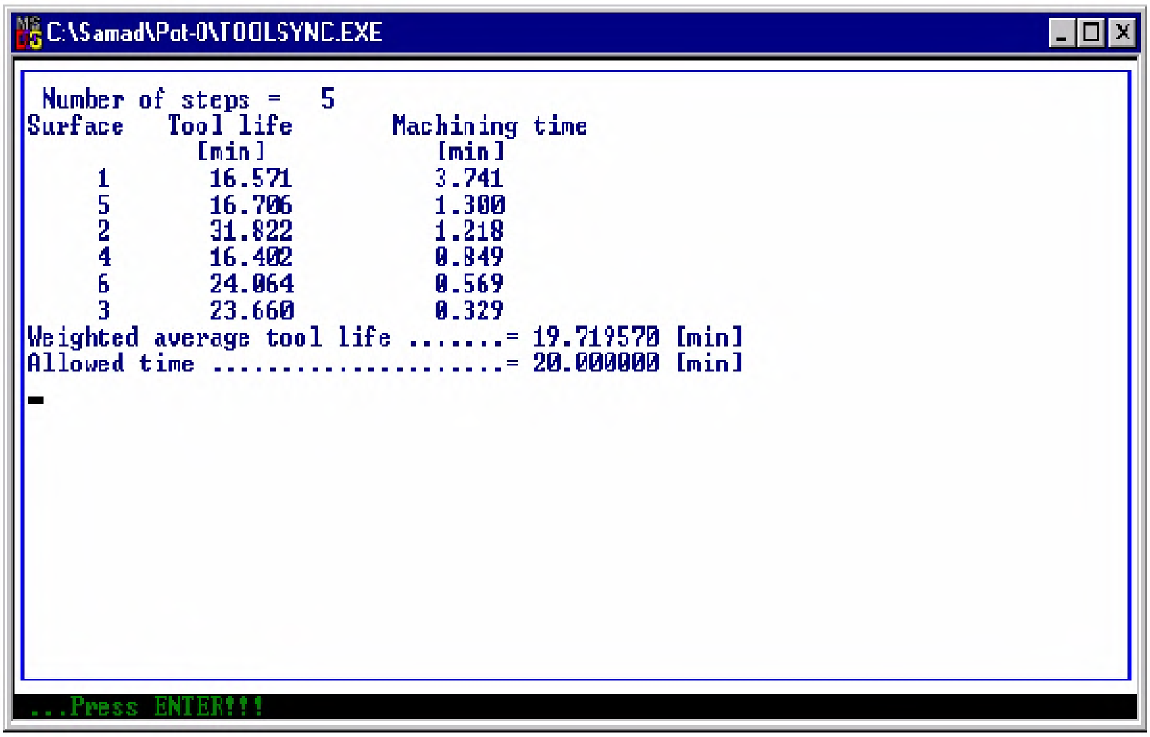


Fig.5.16. The fifth step of optimization where the average tool life increasing along with increasing the local tool life and machining time at the fifth step

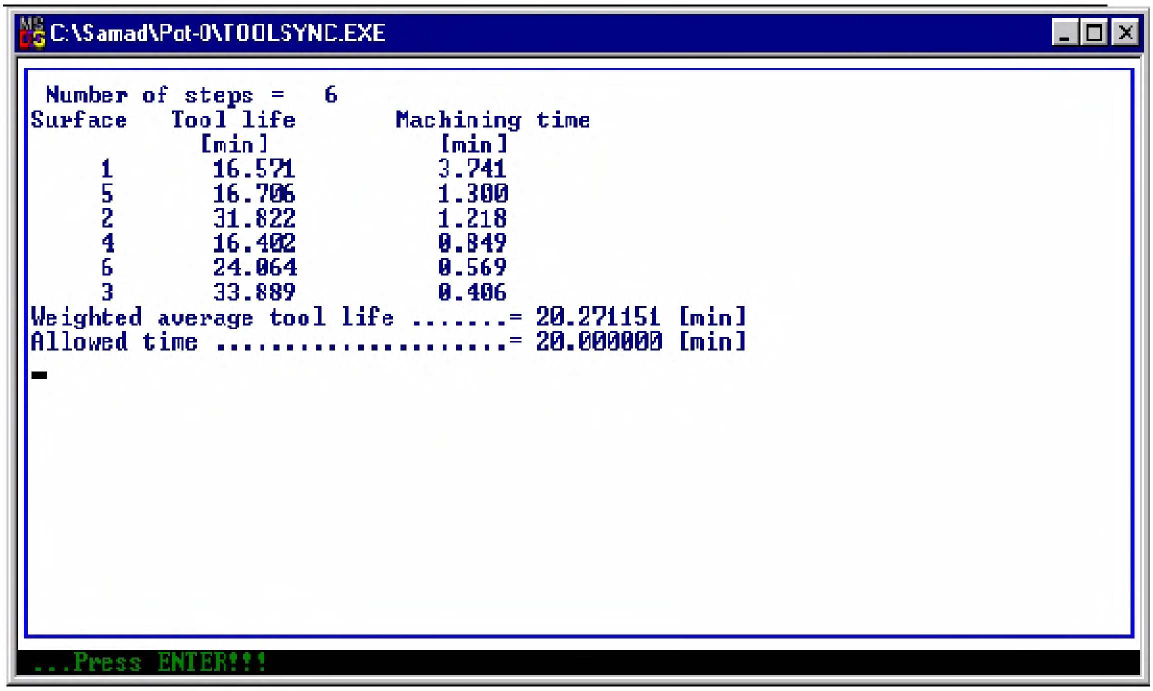


Fig.5.17. The sixth step of optimization where the average tool life increasing along with increasing the local tool life and machining time at the sixth step

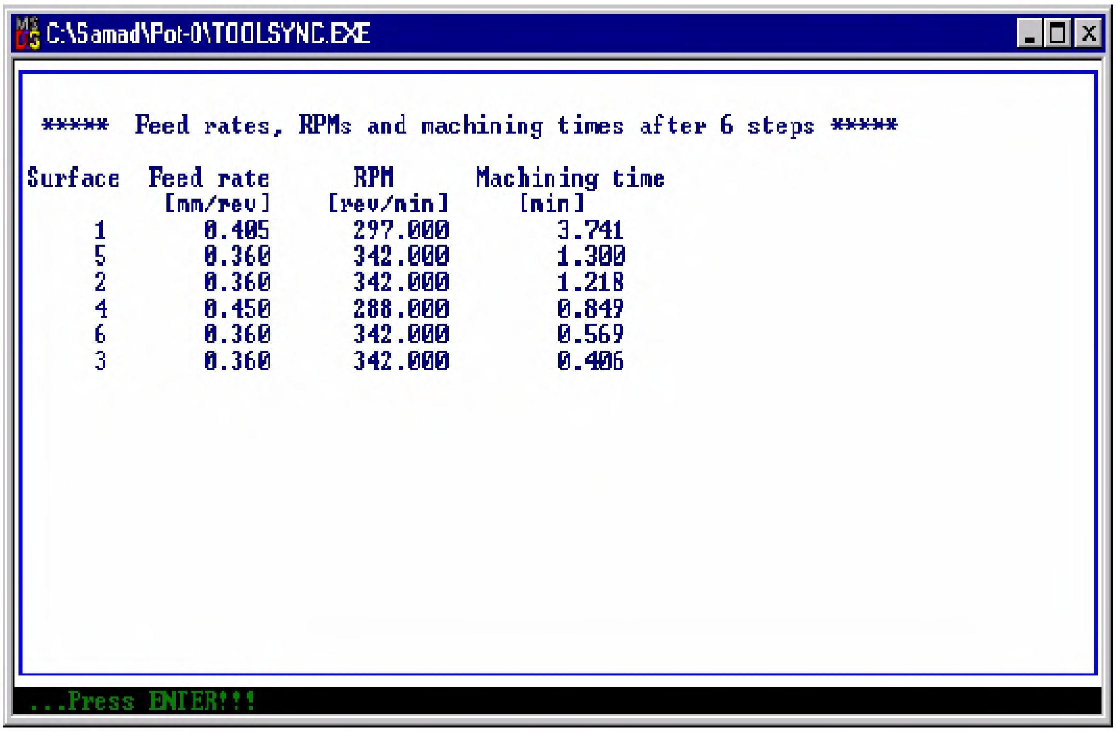


Fig.5.18. The end result of optimization where the feed rate mm/rev and spindle speed revolution/minute have been decreased with ten percent and the surfaces have been arranged in accordance with decreasing machining times.

Secondary optimization with the additional constraint related to the limit of total machining time of the workpiece

Nomenclature:

D_i : diameters of chain elements [mm]
d_i : depth of cut for the i-th element of the chain [mm]
f_i : feed rate for the i-th element of the chain [mm/rev]
K_Σ : the total cost function of the given operation (tool wear and machining costs) [HUF]
K_i : cost of given operation for the i-th layer [HUF]
k : specific costs of workplace (energy, labour cost, amortization, etc.) [HUF/min]
L_i : length of the i-th element of the chain [mm]
m : Taylor constant exponent for tool life
Q_i : the rate of stock-removal for the i-th layer [cm^3/min]
q : inverse of Taylor constant m
R_i : a new macro-parameter depending on the tool characteristics, depth of cut and feed rate for the i-th layer to be removed [cm^3/min]
t_m : total machining time on the base of primary optimization (it can be calculated by means of local optimum parameter values from layer to layer according to the heuristic removal of stock plan) [min]
$t_{m,i}$: machining time for the i-th layer [min]
t_{ml} : limit of total machining time proposed by dispatcher from some kind of organization aspect [min]
τ_i : the cost-equivalent time function for the i-th layer [min/cm^3]
V_i : the volume to be removed for the i-th layer [cm^3]
V_Σ : the sum of the volume to be removed [cm^3]
v_i : cutting speed for the i-th element of the chain [m/min]
z : number of chain elements
λ : Lagrange-multiplier (constant)
HUF : Hungarian Forint.

It is well known that up-to date companies try to increase their productivity, to face rapidly changing market conditions, to improve product design, and to increase product quality for better customer satisfaction in time. But it will not be possible if they do not consider any optimal strategy for production of the goods. The new method aims at *determination of optimum rate of the stock removal factor* Q_i (cm^3/min). It works out based on *the total cost of the given operation* K_Σ (HUF) [35, 36, 30, 12] as an *objective function*, taking into consideration the limit of total machining time t_{ml} (min) as a *constraint* valid for the operation as a whole. *We assume that the dispatcher s time limit related to the total machining time of operation in question is realizable. For example it is based on empiric considerations from the workshop.*

To solve the problem a mathematical model based on *Lagrange multiplier* method has been applied. The derivation of the mathematical model results in optimum rate of stock removal factor, which is independent of cutting parameters (depth of cut, feed rate and cutting speed). It means that increasing cutting speed results in decreasing depth of cut and feed rate or vice versa.

Then it can be concluded that the rate of stock removal factor remains the same for all the layers. This result is also very important when the turning diameter is small, then it is obvious that the smaller the diameter the greater the cutting speed, but as the rate of the stock removal factor is the same for the all the layers, then in this case the depth cut and feed rate should be decreased. This is an advanced solution for optimization of cutting processes based on the rate of stock removal factor.

6.1. The mathematical model of the new optimization method

Let us introduce the objective function $\boldsymbol{K_\Sigma}$ (HUF) [35, 36, 30,]:

$$K_\Sigma = \sum_{i=1}^{z} K_i = k\sum_{i=1}^{z} \tau_i V_i = k\sum_{i=1}^{z}\left(\frac{V_i}{Q_i} + V_i\frac{Q_i^{q-1}}{R_i^q}\right) \quad \text{[HUF]}. \qquad (6.1)$$

The aim is to determine the optimum rate of stock removal factor Q_i which can be obtained from the objective function (6.1) taking into consideration an additional constraint related to total machining time of the workpiece.

The related conditional equation in this respect is as follows:

$$\sum_{i=1}^{z} t_{m,i} = t_m \le t_{ml} \quad \text{[min]}, \qquad (6.2)$$

The conditional equation (the constraint (6.2)) may be considered as follows:

$$\sum_{i=1}^{z} t_{m,i} - t_{ml} = 0 \quad \text{[min]}. \qquad (6.3)$$

Let us apply *Lagrange multiplier* to (6.1) and (6.3) and to denote it with Φ, and then we will have the following:

$$K \to \Phi = k\sum_{i=1}^{z} V_i\left(\frac{1}{Q_i} + \frac{Q_i^{q-1}}{R_i^q}\right) + \lambda.k\sum_{i=1}^{z}\frac{V_i}{Q_i} - \lambda.kt_{ml}. \tag{6.4}$$

Where from the literature [35] we can get the following:

$$t_{m,i} = \frac{V_i}{Q_i} \quad \frac{\text{cm}^3}{\left(\frac{\text{cm}^3}{\text{min}}\right)} \quad \to [\text{min}]. \tag{6.5}$$

Let us derivate (6.4) with respect to the rate of stock removal factor Q_i, and then we will have the following:

$$\left.\frac{\partial \Phi}{\partial Q_i}\right|_{R_i = const} = \frac{\partial}{\partial Q_i} k\sum_{i=1}^{z} V_i\left(\frac{1}{Q_i} + \frac{Q_i^{q-1}}{R_i^q}\right) + \frac{\partial}{\partial Q_i}\lambda.k\sum\frac{V_i}{Q_i} - \frac{\partial}{\partial Q_i}\lambda.kt_{ml} \tag{6.6}$$

After summarizing we get:

$$\frac{\partial \Phi}{\partial Q_i} = -k\frac{V_i}{Q_i^2} + kV_i(q-1)\frac{1}{R_i^q}Q_i^{q-2} - \lambda.k\frac{V_i}{Q_i^2}. \tag{6.7}$$

Let us solve the equation for $\frac{\partial \Phi}{\partial Q_i} = 0$ then we have:

$$\frac{\partial \Phi}{\partial Q_i} = 0 \to -k\frac{V_i}{Q_i^2} + kV_i(q-1)\frac{1}{R_i^q}Q_i^{q-2} - \lambda.k\frac{V_i}{Q_i^2} = 0. \tag{6.8}$$

Dividing both sides of (6.8) by ($k \neq 0$) we get:

$$-\frac{V_i}{Q_i^2} + V_i(q-1)\frac{1}{R_i^q}Q_i^{q-2} - \lambda\frac{V_i}{Q_i^2} = 0. \tag{6.9}$$

Rearranging (6.9), then we will get the following:

$$-\frac{V_i}{Q_i^2}(1+\lambda) + V_i(q-1)\frac{1}{R_i^q}Q_i^{q-2} = 0. \tag{6.10}$$

Multiplying both sides of (6.9) by $\frac{Q_i^2}{V_i} \neq 0$ we get:

$$-(1+\lambda)+(q-1)\frac{1}{R_i^q}Q_i^q = 0. \tag{6.11}$$

Multiplying (6.11) by constant $R_i^q \neq 0$ we get the following:

$$-(1+\lambda)R_i^q + (q-1)Q_i^q = 0. \tag{6.12}$$

Let us solve equation (6.12) for Q_i, and then we can get the following:

$$Q_i^q = \frac{(1+\lambda)R_i^q}{q-1}. \quad [\text{cm}^3/\text{min}] \tag{6.13}$$

And the end result for Q_i will be the following:

$$Q_i = R_i\left(\frac{1+\lambda}{q-1}\right)^{\frac{1}{q}} \quad [\text{cm}^3/\text{min}]. \tag{6.14}$$

Let us substitute (6.14) and $t_{m,i}$ with $\frac{V_i}{Q_i}$ in conditional equation (6.3), then we obtain the following relationship:

$$\sum_{i=1}^{z}\frac{V_i}{Q_i} - t_{ml} = 0 \rightarrow \sum_{i}^{z}\frac{V_i}{R_i}\left(\frac{q-1}{1+\lambda}\right)^{\frac{1}{q}} - t_{ml} = 0. \tag{6.15}$$

Arranging (6.15) equation we get the following:

$$(q-1)^{\frac{1}{q}}\sum_{i=1}^{z}\frac{V_i}{R_i} = t_{ml}(1+\lambda)^{\frac{1}{q}}. \tag{6.16}$$

In (6.16) the only unknown is λ, then let solve it for λ value:

$$\lambda = \frac{q-1}{t_{ml}^q}\left(\sum_{i=1}^{z}\frac{V_i}{R_i}\right)^q - 1. \tag{6.17}$$

Let us rearrange (6.14) we will get the following:

$$\left(\frac{Q_i}{R_i}\right)^q = \frac{1+\lambda}{q-1}. \tag{6.18}$$

Solving (6.18) for λ we get the following:

$$(q-1)\left(\frac{Q_i}{R_i}\right)^q - 1 = \lambda. \tag{6.19}$$

Comparing (6.19) and (6.17) we get the following:

$$(q-1)\left(\frac{Q_i}{R_i}\right)^q - 1 = \frac{(q-1)}{t_{ml}^q}\left(\sum_{i=1}^{z}\frac{V_i}{R_i}\right)^q - 1 \tag{6.20}$$

Summarizing (6.20) the following equation results:

$$t_{ml}^q\left(\frac{Q_i}{R_i}\right)^q = \left[\sum_{i=1}^{z}\left(\frac{V_i}{R_i}\right)\right]^q \tag{6.21}$$

After extraction of a root according to q from (21) we get:

$$t_{ml}\frac{Q_i}{R_i} = \sum_{i=1}^{z}\frac{V_i}{R_i} = \frac{V_1}{R_1} + \frac{V_2}{R_2} + \ldots\ldots + \frac{V_i}{R_i} + \ldots\ldots + \frac{V_Z}{R_Z}. \tag{6.22}$$

Because on the left hand side of (6.22) i means an index optional but fixed after selection, for the sake of avoiding misunderstanding, it is expedient to use a different running index on the right hand side:

$$t_{ml}\frac{Q_i}{R_i} = \sum_{j=1}^{Z}\frac{V_j}{R_j}, \tag{6.22a}$$

hence

$$Q_i = \frac{R_i}{t_{ml}}\sum_{j=1}^{Z}\frac{V_j}{R_j}. \tag{6.23}$$

In that special case when R_i is the same for all the layers to be removed, i.e. $R_i = R_j$, we have:

$$Q_i = \frac{\sum_{j=1}^{Z} V_j}{t_{ml}} = \frac{V_\Sigma}{t_{ml}}. \tag{6.24}$$

The resultant equation (6.24) means that the rate of stock removal factor Q_i also is the same for all the layers. For example if we consider a chain of the elements to be machined and supposing that the diameters of the chain elements are not very big then the following conditions can satisfy the value of the rate of stock removal factor. This solution may have a *trivial* meaning but it is possible to develop it by adding the *tool change time* to the Lagrange function, because at this solution the tool change time has not been taking into consideration.

$$Q_1 = Q_2 = Q_3 = \ldots\ldots\ldots\ldots = Q_i = \frac{V_\Sigma}{t_{ml}}. \tag{6.25}$$

Discussion:

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

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

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

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

Secondary optimization with the additional constraint related to the average tool life calculated on the base of local tool lives and local machining times

Nomenclature:

C_s	: a complex constant for the tool characteristics and depth of cut
C_v	: first Taylor constant
D_i	: diameters of chain elements [mm]
d_i	: depth of cut for the i-th chain element [mm]
f_i	: feed rate for the i-th chain element [mm/rev]
$H(X_k)$	: Hesse matrix
K_Σ	: the total cost of given operation [HUF]
K_{sb}	: total cost of using the cutting tool (purchase, storage, waste) [HUF]
k	: specific costs of workplace (energy, labour, amortization, etc.) [HUF/min]
L_i	: length of i-th element of the chain [mm]
m	: Taylor constant exponent for tool life
N_{el}	: number of tool edges
Q_i	: the rate of stock-removal for the i-th element [cm^3/min]
q	: inverse of Taylor constant m
R_i	: a new macro-parameter depending on the tool characteristics, depth of cut and feed rate for the i-th layer to be removed [cm^3/min]
S_K	: correction vector
T_i	: local tool life for the i-th element [min]
$T_{w,allowed,}$	: maximum weighted average tool life allowed to be utilized [min]
T_w	: prescribed weighted average tool life in changing circumstances [min]
t_m	: total machining time [min]
$t_{m,i}$	: machining times for the i-th element [min]
t_{cs}	: time necessary to change the tool edge [min]
τ	: the cost-equivalent time [min/cm^3]
V_i	: the volume to be removed for the i-th element [cm^3]
V_Σ	: the sum of the volume to be removed [cm^3]
v_i	: cutting speed for the i-th chain element [m/min]
x_v	: third Taylor constant
y_v	: second Taylor constant

z	: number of chain elements
λ	: Lagrange-multiplier (constant)
$\psi(Q_i,\lambda)$	: Lagrange function
$\psi'(Q_i,\lambda)$	: vector gradient of function $\psi(Q_i,\lambda)$
HUF	: Hungarian Forint.

The new method of optimization works based on variable rate of stock removal factor Q_i (cm^3/min). It aims at *minimizing the total cost of the given operation* K_Σ (HUF) as *the objective function*, [35, 36, 30]. The *constraint* for this purpose is *maximum weighted average tool life that is allowed to be utilized* $T_{w,allowed} \geq T_w$ (min). The macro- parameter R (cm^3/min) is calculated based on the given input parameters and $T_{w,\ allowed}$ (min) is calculated on the base of local tool lives T_i [min] and machining times $t_{m,i}$ (min). To find a suitable solution for the new optimization problem, *Lagrange-multiplier* [2] method has been used.

Applying Lagrange multiplier method results in a new function denoted by $\psi(Q_i,\lambda)$.

The derivation of function $\psi(Q_i,\lambda)$ with respect to the rate of the stock- removal factor Q_i is the gradient vector of this function.

The gradient vector $\psi'(Q_i,\lambda)$ of function $\psi(Q_i,\lambda)$. results in a non-linear system of equations. The system has got $N+1$ unknowns and there is a need to apply a numerical method to solve the problem for Q_i and λ.

The numerical solution based on *multidimensional Newton-method* [2] has been applied to develop a program to calculate *the validity range of Lagrange-multiplier* and *the rates of stock removal factors* Q_i too.

After solving the system of non-linear equations for Q_i and λ, the optimised value of *the total cost of the given operation* K_Σ (HUF) is obtained.

The *process needs iteration steps* by computer program, which turns the gradient vector $\psi'(Q_i,\lambda)$ to zero. The new method of optimisation solves multidimensional problems in cutting processes.

7.1. The mathematical model of the new optimization method

The general formula used for cost equivalent time function τ (min/cm^3) is as follows: [35, 36, 30]:

$$\tau = \frac{1}{Q} + \frac{Q^{q-1}}{R^q} \quad [\text{min/ cm}^3], \tag{7.1}$$

where the objective function is as follows:

$$K_\Sigma = \sum_{i=1}^{z} K_i = k\sum_{i=1}^{z} \tau_i V_i = k\sum_{i=1}^{z}\left(\frac{V_i}{Q_i} + V_i\frac{Q_i^{q-1}}{R_i^q}\right) \quad [\text{min/cm}^3]. \quad \Rightarrow \text{minimum} \tag{7.2}$$

The aim is to minimize the objective function (7.2) taking into consideration the following conditional equation (7.3).

$$T_{w,allowed} \geq T_w \qquad [\text{min}]. \tag{7.3}$$

If we consider the maximum utilization of the weighted average tool life, which is allowed to be utilized then we can have the following:

$$T_{w,allowed} - T_w = 0 \qquad [\text{min}], \tag{7.4}$$

where:

$$T_{w,allowed} = T_w = \frac{\sum_{i=1}^{z} T_i . t_{m,i}}{\sum_{i=1}^{z} t_{m,i}} \quad [\text{min}]. \tag{7.5}$$

Let us substitute $T_{w,\ allowed}$ (7.5) in (7.4), and then we will have the following equation:

$$\frac{\sum_{i=1}^{z} T_i . t_{m,i}}{\sum_{i=1}^{z} t_{m,i}} - T_w = 0. \tag{7.6}$$

Let us express machining times $t_{m,i}$ and local tool lives T_i in terms of rate of stock removal factor Q_i and macro-parameter R_i, then we will have the following:

$$t_{m,i} = t_{m,i}(Q_i) \tag{7.7}$$

$$T_i = T_i(Q_i, R_i) \tag{7.8}$$

Equation (7.7) may be considered in terms of Q_i as follows [35]:

$$t_{m,i} = \frac{V_i}{Q_i} \quad [\text{min}]. \tag{7.9}$$

Let us also express T_i in terms of Q_i using Taylorian tool life equation as follows:

$$T_i = \left(\frac{C_v}{d_i^{x_v} . f_i^{y_v} . v_i} \right)^{\frac{1}{m}} \quad [\text{min}]. \tag{10}$$

Let us express (7.10) as follows:

$$T_i = \left(\frac{C_v}{d_i^{x_v} . f_i^{y_v} . v_i} . \frac{d_i . f_i}{d_i . f_i} \right)^{\frac{1}{m}} \quad [\text{min}]. \tag{11}$$

As is known $d_i f_i v_i = Q_i$, substituting this value of Q_i in (7.11) we will have the following equation:

$$T_i = \left(\frac{C_v . d_i^{1-x_v} . f_i^{1-y_v}}{Q_i} \right)^{\frac{1}{m}} \quad [\text{min}]. \tag{7.12}$$

Further more the macro-parameter R is as follows:

$$R_i = C_s . f_i^{1-y_v} \quad [\text{cm}^3/\text{min}]. \tag{7.13}$$

Where machining cost unit per minute is as follows:

$$C_s = \frac{C_v . d_i^{1-x_v}}{\left[\frac{K_{sb}}{k.N_{el}} + t_{cs} \right]^m} \tag{7.14}$$

We can express equation (7.13) as follows:

$$f_i^{1-y_v} = \frac{R_i}{C_s}. \tag{7.15}$$

And (7.14) as follows:

$$C_v . d_i^{1-x_v} = C_s \left[\frac{K_{sb}}{k.N_{el}} + t_{cs} \right]^m . \tag{7.16}$$

For the sake of simplicity let us denote $\left[\dfrac{K_{sb}}{k.N_{el}}+t_{cs}\right]$ with A, then (7.16) turns to be as follows:

$$C_v.d_i^{1-x_v} = C_s\left[\frac{K_{sb}}{k.N_{el}}+t_{cs}\right]^m = C_s A^m \tag{7.17}$$

Let us substitute (7.15) and (7.17) in (7.12), then we will have the following:

$$T_i = \left(\frac{C_s.A^m.R_i}{C_s.Q_i}\right)^{\frac{1}{m}} \tag{7.18}$$

After summarizing (7.18) we will get the following:

$$T_i = \left(\frac{A^m.R_i}{Q_i}\right)^{\frac{1}{m}} \tag{7.19}$$

A^m is a constant, then we may express (7.19) in terms of Q_i and R_i as follows:

$$T_i = A\left(\frac{R_i}{Q_i}\right)^{\frac{1}{m}} \tag{7.20}$$

Let us substitute $q = 1/m$, then (7.20) will be as follows:

$$T_i = A\left(\frac{R_i}{Q_i}\right)^q \tag{7.21}$$

Substituting (7.9) and (7.21) in conditional equation (7.6) we will get the following equation:

$$\frac{A\sum_{i=1}^{z}\left(\frac{R_i}{Q_i}\right)^q \cdot\left(\frac{V_i}{Q_i}\right)}{\sum_{i=1}^{z}\left(\frac{V_i}{Q_i}\right)} - T_w = 0. \tag{7.22}$$

Let us apply Lagrange multipliers method to the objective function (7.2) and the new conditional equation (7.22) and denote it with $\psi(Q_i,\lambda)$ as follows:

$$\psi(Q_i,\lambda) = k\sum_{i=1}^{z}\left(\frac{1}{Q_i}+\frac{Q_i^{q-1}}{R_i^q}\right)V_i + \lambda.k\left(\frac{A\sum_{i=1}^{z}\left(\frac{R_i}{Q_i}\right)^q\cdot\left(\frac{V_i}{Q_i}\right)}{\sum_{i=1}^{z}\left(\frac{V_i}{Q_i}\right)} - T_w\right) \Rightarrow \text{minimum}$$

(7.23)

Let us derivate (7.23) with respect to Q_i, then we will have the following:

$$\left.\frac{\partial\psi}{\partial Q_i}\right|_{R_i^q=const} = \frac{\partial}{\partial Q_i}\left[k\sum_{i=1}^{z}\left(\frac{1}{Q_i}+\frac{Q_i^{q-1}}{R_i^q}\right)V_i\right] + \lambda.k\frac{\partial}{\partial Q_i}\left(\frac{A\sum_{i=1}^{z}\left(\frac{R_i}{Q_i}\right)^q\cdot\left(\frac{V_i}{Q_i}\right)}{\sum_{i=1}^{z}\left(\frac{V_i}{Q_i}\right)} - T_w\right) = 0.$$

(7.24)

Derivation (7.24) turns into a highly non-linear system of equations, which needs a multidimensional numerical method to solve it.

Equation (7.22) as the second part of (7.23) is fraction type and it can be derived as the following derivation technique [2]:

$$\left(\frac{u}{v}\right)' = \left(\frac{u'v-uv'}{v^2}\right)$$

Note: The full derivation of (7.23) can be found in APPENDIX 2.

7.2. Algorithm for solving Q_i and λ

The main idea of the method is as follows:

Let us denote the derivation of function $\psi(Q_i,\lambda)$ with its gradient vector $\psi'(Q_i,\lambda)$. The aim is to solve the non-linear system of equations to find Q_i and λ, so that, the gradient vector $\psi'(Q_i,\lambda)$ of function $\psi(Q_i,\lambda)$ should turn to zero as follows:

$$\frac{\partial \psi}{\partial Q_1} = \psi'(Q_1, \lambda) = 0.$$
$$\frac{\partial \psi}{\partial Q_2} = \psi'(Q_2, \lambda) = 0.$$
$$\frac{\partial \psi}{\partial Q_3} = \psi'(Q_3, \lambda) = 0.$$
$$.$$
$$.$$
$$\frac{\partial \psi}{\partial Q_z} = \psi'(Q_z, \lambda) = 0.$$

Let us denote the *k-th* iteration in the method of solution (numerical method of solution) with X_k for range of the values for Q_i and λ.

We start the first step of the method from X_0 where $X_0 = (Q_1=Q_2=Q_3= \quad Q_z = 240, \lambda=16)$. These values of X_0 were chosen from practical observations. In each step we modify X_k by S_k obtaining $X_{k+1}=X_k+S_k$ (for example in case $k = 0$, then $X_1 = X_0 + S_0$), where S_k is the vector obtained as a solution in each step from a system of <u>*linear equations*</u> as follows:

$$H(X_k)S_k = -\psi'(X_k)$$

$$\begin{pmatrix} \\ \\ Hesse\,Matrix \\ \\ \\ \end{pmatrix}\begin{pmatrix} S_1 \\ S_2 \\ S_3 \\ \\ S_n \end{pmatrix} = -\begin{pmatrix} \psi'_1 \\ \psi'_2 \\ \psi'_3 \\ . \\ \psi'_z \end{pmatrix},$$

where $H(X_k)$ is called <u>*Hesse*</u> matrix of the function $\psi(Q_i,\lambda)$ and as previously mentioned S_k is the vector. This matrix is constructed from the second derivative $H(X_k) = \frac{\partial^2 \psi}{\partial X_i \partial X_j}$ of function $\psi(Q_i,\lambda)$ and the second derivatives in Hesse matrix were computed numerically in the program. The method converges not too fast. (Please see APPENDIX 3.)

7.3. Inputs and technological parameters for developing a program

The geometry of the workpiece for turning operation is known (Please see Fig.5.1). The volume V_i to be removed is determined based on the following equation:

$$V_i = \pi.10^{-3}.D_i.d_i.l_i \quad [\text{cm}^3].$$

The macro-parameter R is calculated as follows [35]:

$$R_i = C_s.f_i^{1-y_v} \quad [\text{cm}^3/\text{min}].$$

where:

$$C_s = \frac{C_v.d_i^{1-x_v}}{\left(\frac{K_{sb}}{k.N_{el}} + t_{cs}\right)^m}$$

And the inverse of Taylor constant is $q = 1/m$.

<u>**Note**</u>: All the mentioned parameters are inputs and the computer program calculates the equations automatically. (Please see the nomenclatures related to input parameters).

7.4. Outputs of the developed program

The most important outputs of the program are Q_i and λ. Knowing λ and the rate of stock removal factors Q_i , <u>*the optimum total cost of the given operation*</u> K_Σ [HUF] is obtained. The other important output is the gradient of the objective function that converges to zero.

7.5. Example of the running program

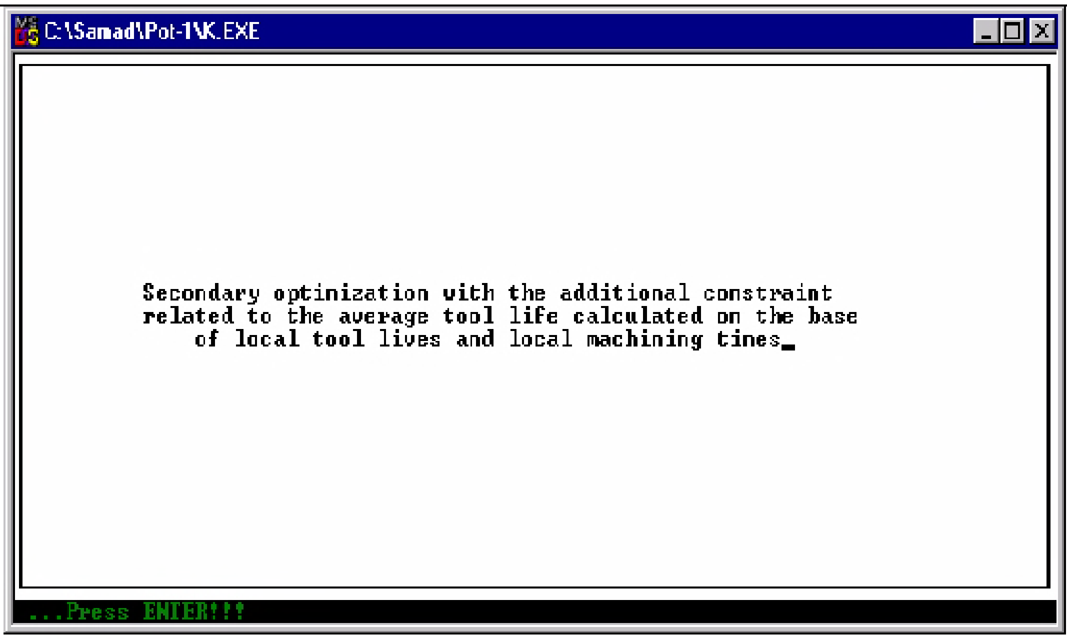


Fig.7.1. Example of starting the program procedure

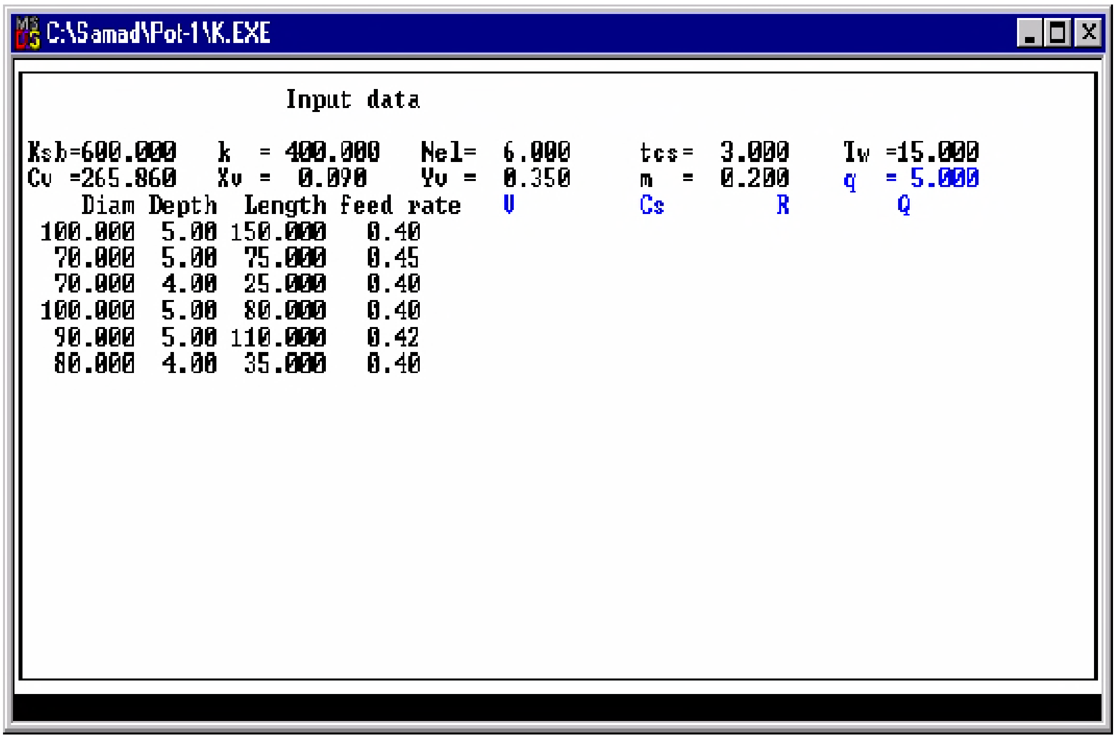


Fig.7.2. The input data

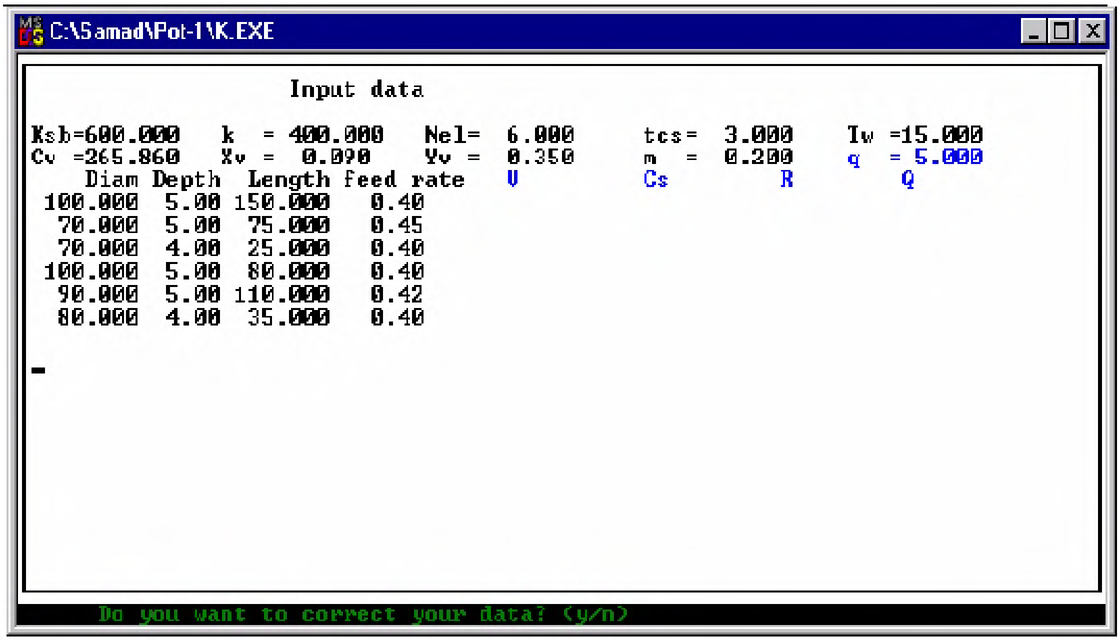


Fig.7.3. An example of checking the correction of the given data

At this step program enquires the user whether he or she wants to correct any false data or not. If the given data are correct, then only by entering "No" the process is continued, otherwise entering "Yes" make it possible to correct any wrong data. After each correction entering is required. The row keys position the cursor.

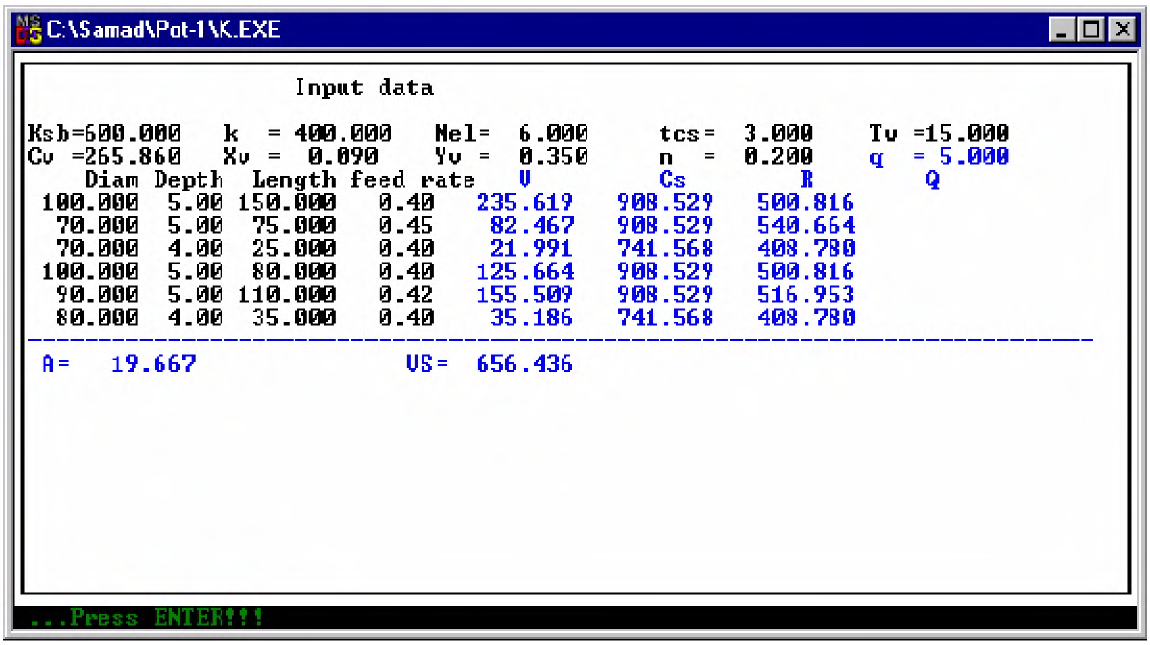
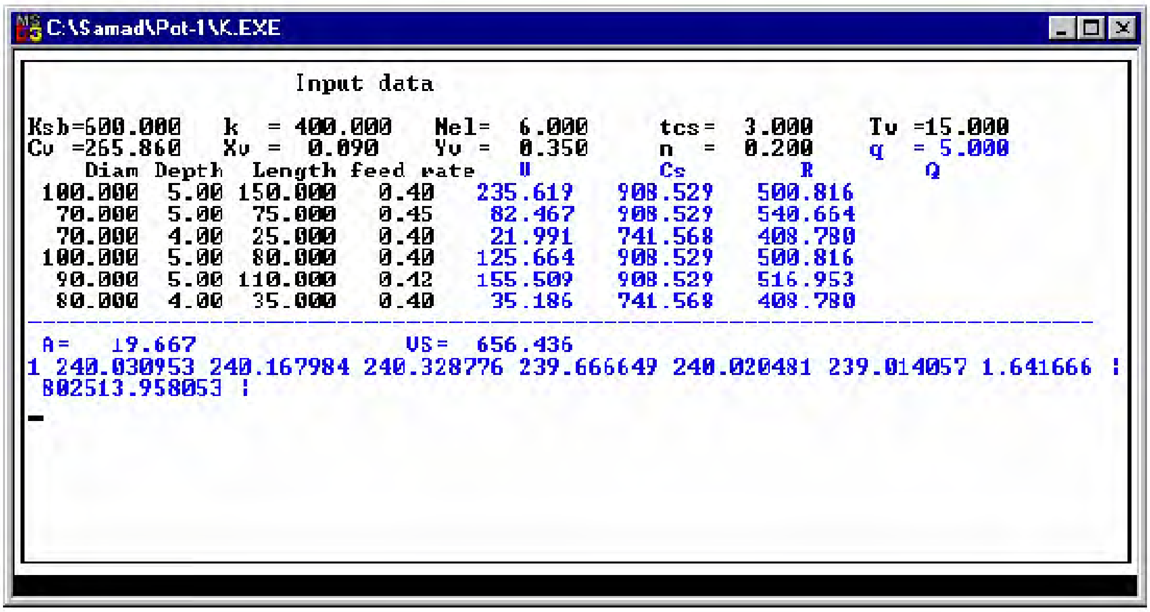


Fig.7.4. The calculated value of the total volume to be removed V_{Σ} (cm^3) unit cost/min C_s, macro- parameter R (cm^3/min) and A

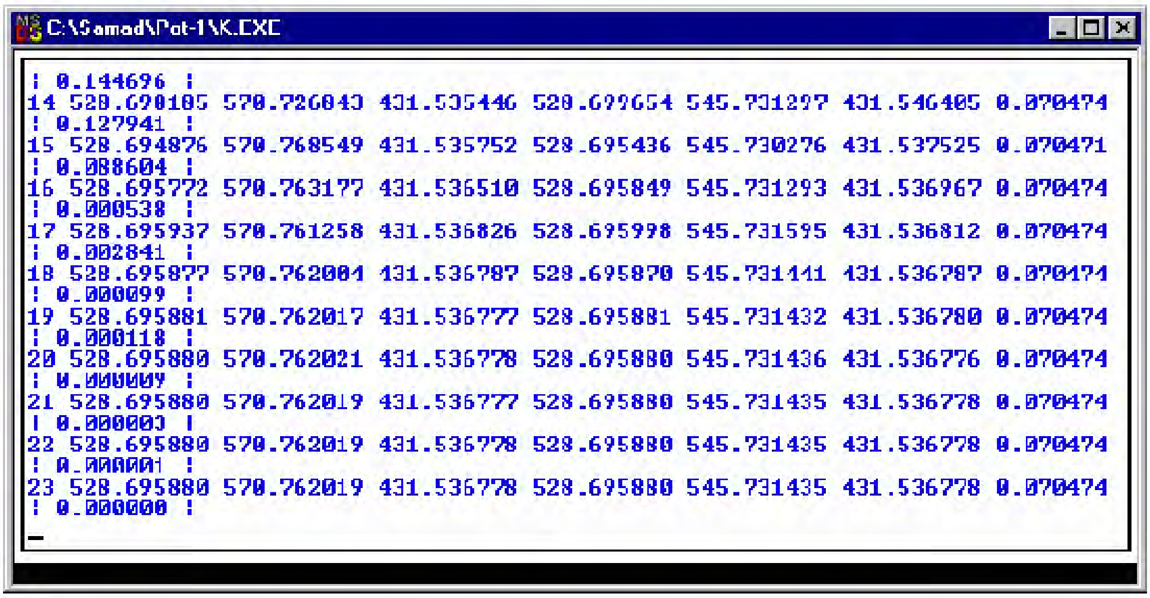


```
C:\Samad\Pot-1\K.EXE
                        Input data

Ksb=600.000   k  = 400.000   Nel=  6.000     tcs=  3.000    Tv =15.000
Cv =265.860   Xv =  0.090    Yv =  0.350     n  =  0.200    q  = 5.000
    Diam Depth  Length feed rate    U          Cs        R         Q
 100.000  5.00 150.000   0.40   235.619   908.529   500.816
  70.000  5.00  75.000   0.45    82.467   908.529   540.664
  70.000  4.00  25.000   0.40    21.991   741.568   408.780
 100.000  5.00  80.000   0.40   125.664   908.529   500.816
  90.000  5.00 110.000   0.42   155.509   908.529   516.953
  80.000  4.00  35.000   0.40    35.186   741.568   408.780
--------------------------------------------------------------------------------
 A=   19.667                VS=   656.436
1 240.030953 240.167984 240.328776 239.666649 240.020481 239.014057 1.641666 !
 802513.958053 !
```

Fig.7.5. The first iteration starting to calculate Q_i, λ and $\psi'(Q_i,\lambda)$

Note: The first column on the screen is the number of iteration. The next six columns are Q_1, Q_2, Q_3, Q_4, Q_5, and Q_6 .The remaining two columns are λ and $\psi'(Q_i,\lambda)$. The iteration goes on till $\psi'(Q_i,\lambda)$ converges to zero.



```
C:\Samad\Pot-1\K.EXE
! 0.144696 !
14 528.690105 570.726043 431.535446 528.699654 545.731297 431.546405 0.070474
! 0.127941 !
15 528.694876 570.768549 431.535752 528.695436 545.730276 431.537525 0.070471
! 0.088604 !
16 528.695772 570.763177 431.536510 528.695849 545.731293 431.536967 0.070474
! 0.000538 !
17 528.695937 570.761258 431.536826 528.695998 545.731595 431.536812 0.070474
! 0.002841 !
18 528.695877 570.762004 431.536787 528.695870 545.731441 431.536787 0.070474
! 0.000099 !
19 528.695881 570.762017 431.536777 528.695881 545.731432 431.536780 0.070474
! 0.000118 !
20 528.695880 570.762021 431.536778 528.695880 545.731436 431.536776 0.070474
! 0.000009 !
21 528.695880 570.762019 431.536777 528.695880 545.731435 431.536778 0.070474
! 0.000003 !
22 528.695880 570.762019 431.536778 528.695880 545.731435 431.536778 0.070474
! 0.000001 !
23 528.695880 570.762019 431.536778 528.695880 545.731435 431.536778 0.070474
! 0.000000 !
```

Fig.7.6. The screen shows the last iteration step

Note: If we compare Fig.7.5 with Fig.7.6. We can realize that Q_i are increasing, while λ and $\psi'(Q_i,\lambda)$ are decreasing, which means that program very efficiently solves the system of equations and make it possible that $\psi'(Q_i,\lambda)$ to turn into zero. It is to remind that continuing the iteration done by the help of 'space key'. It means that we have to push the space key for the further process.

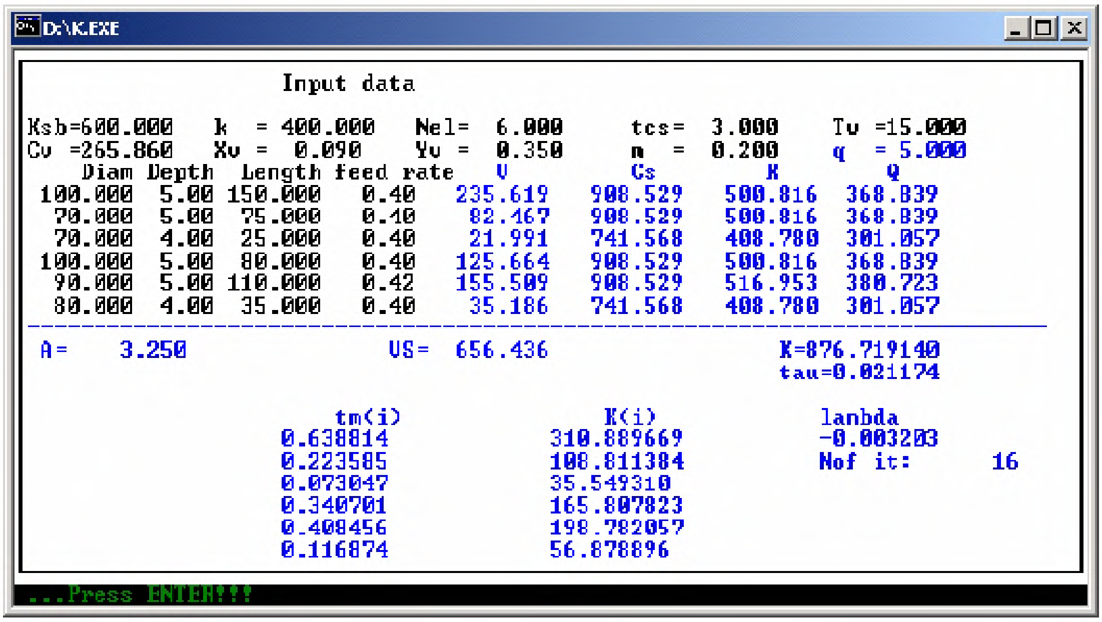


Fig.7.7. The result of the computation by mean s of iterations

The program after solving the *non-linear system of equations for the optimum rate of stock removal factor* Q_i (cm^3/min) and λ (constant) searches for *the optimum value of the total cost of operation for each chain element* K_i (HUF), then it calculates *the optimum total cost of operation* K_Σ (HUF) for the total chain elements.

The local tool life T_i shows that the local tool life is not less than 15 minutes for each chain element.

Here I have to remind that if we calculate the maximum value of weighted average tool life $T_{w,allowed}$ (min) using the machining times for each chain element the result will fulfil the constraint function $T_{w,allowed} - T_w = 0$.

Further more as is shown all the other values have been calculated automatically (for example the total volume to be removed V_{sum} (cm^3), the macro parameter R (min/cm^3), and the machine C_s (cost/min)).

Note: The program uses the total volume to be removed VS instead of V_Σ and K instead of K_Σ. For the notation "A", please refer to equation (7.16).

Considering the geometry of the workpiece to be cut and the given technological parameters, then, the optimum value for the rate of stock removal factor Q_i may be obtained after several number of iterations, it is because the mathematical model of this optimization method results in a high non-linear system of equations and the solution of this kind of system is only done by applying some kind of numerical methods.

In the end the solution results in calculating the optimum values of the rates of stock removal factors based on number of the chain used in the workpiece design. Then the optimum value of the total cost for the given operation obtained.

The program is of very importance as it can be applied for the solution of optimum cutting conditions using the total cost of the given operation as an objective function and in addition the tool life as a constraint.

This procedure considers both managerial and technological aspects in optimization of cutting condition problems, which is the goal.

The program can be integrated in Computer Aided Process Planning (CAPP) in CIM environment.

The new scientific results THESIS

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

Tóth, Tibor has drafted the basic principles for determination of cutting conditions.

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

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

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

1. Tool life synchronization in case of a prescribed average tool life (**Thesis 1**).

2. Secondary Optimization with the additional constraint related to the limit of total machining time of the workpiece (**Thesis 2**).

3. Secondary Optimization with the additional constraint related to the average tool life calculated on the base of local tool lives and local machining times (**Thesis 3**).

THESIS 1

In many machining operations it may prove advantageous to restrict the feed rate and spindle speed within certain limits. In this respect we may say that technological parameters have the best roles, as they control the economical aspects. The optimum determination of cutting parameters depth of cut (d_i), feed rate, (f_i) and cutting speed (v_i) is of a great importance especially for NC/CNC machine tools. This part of the Thesis aims at <u>*optimization of tool life*</u> using appropriate cutting parameters. The workpiece is machined without changing the tip edge. The explanation for the process is as follows (Fig.8.1.):

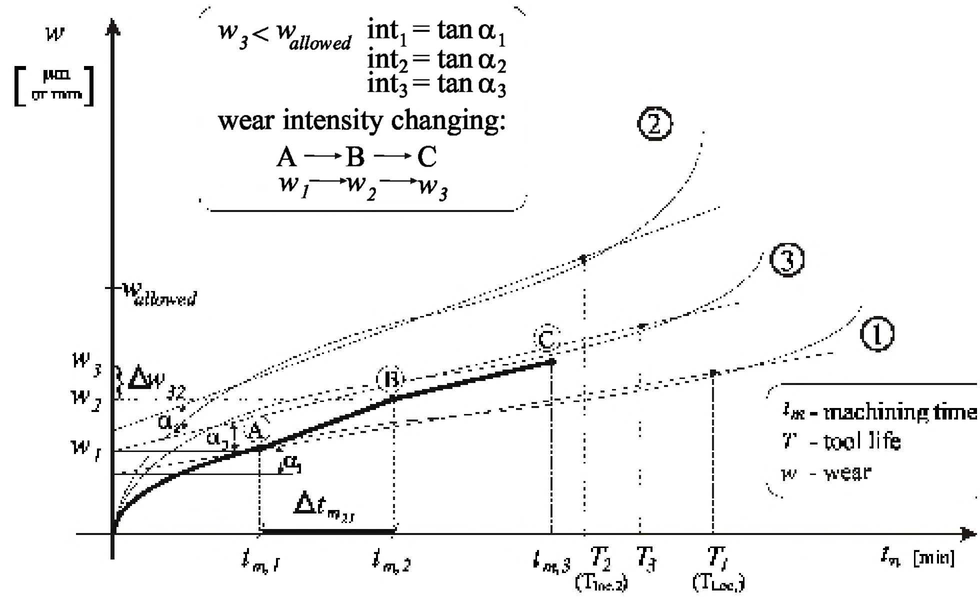


Fig.8.1. Relationships between machining time and tool wear

The given tool edge is used under changeable cutting conditions. For the sake of simplicity we suppose that the edge is used according to the first $w = w(t_m)$ curve until the machining time $t_{m,1}$ (see curve 1, point A).

From this point because of the higher cutting intensity we change the cutting conditions, then the tool wear will follow curve 2 (see phase A→ B, until the machining time $t_{m,2}$).

At the machining time $t_{m,\ 2}$ we also change cutting conditions according to curve 3 until the machining time $t_{m,\ 3}$. Here the wear intensity are denoted by $int_1 = tan\alpha_1$, $int_2 = tan\alpha_2$ and $int_3 = tan\alpha_3$ where the smallest is $int_3 = tan\alpha_3$ in this theoretical relationships.

Then our suggestion is to calculate a weighted average tool life T_w (min) with respect to each local tool life T_i (min) in accordance with its proportional weight. It means that if a layer removal is very time consuming, then the local tool life belonging to it will influence the average tool life proportionally to a greater extent in comparison with another layer removal of which needs smaller time.

At the new method the tool optimization is a loop of reduction of feed rates and spindle speed taking into consideration the weighted average tool life as a constraint and arranging the surfaces in accordance with decreasing machining times. For this purpose and demonstrating the practical use of the new method I have further developed a computer program (Fig.8.2.).

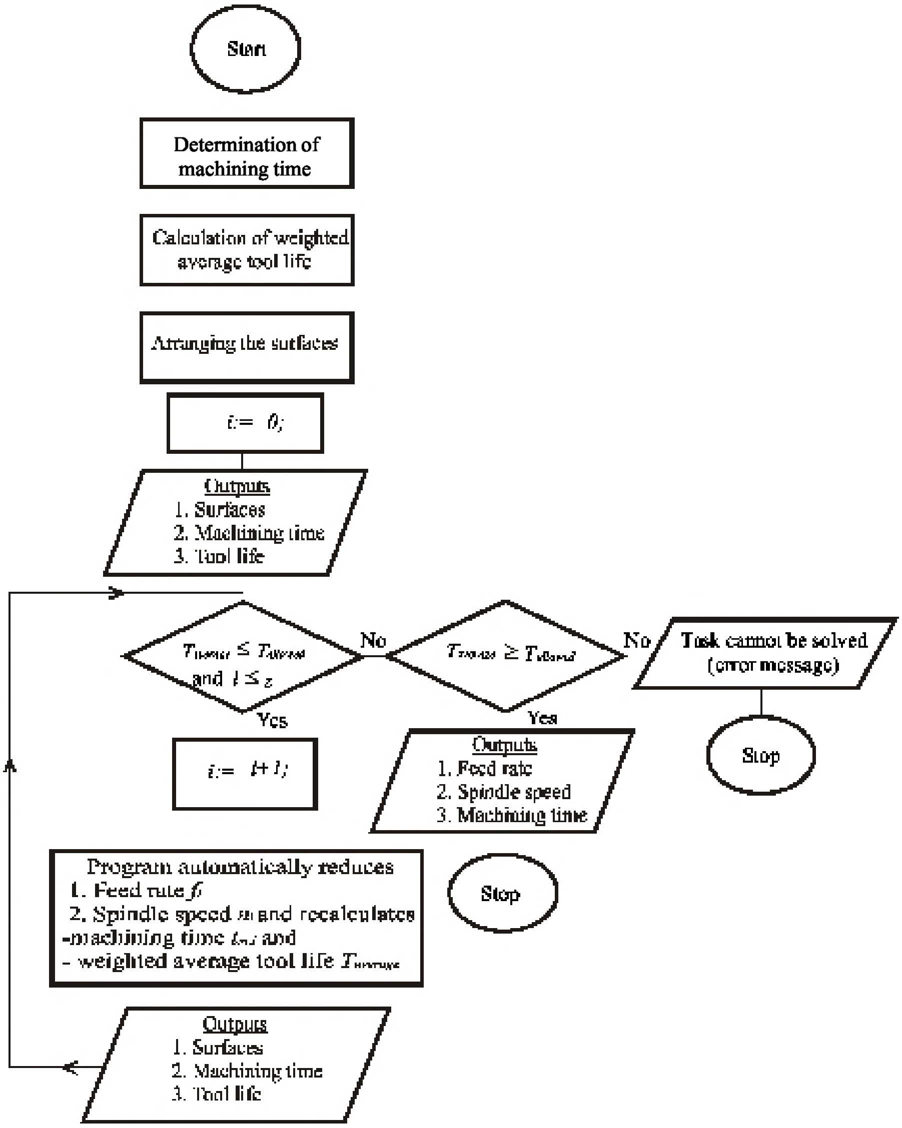


Fig.8.2. Elaboration of an algorithm for tool life synchronization

The results obtained from this trial are decrease in feed rate, decrease in spindle speed and arrangement of surfaces of workpiece to be machined in accordance with decreasing machining times, which in consequence is increasing the tool life.

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

THESIS 2

Based on principles and fundamentals of optimization problems I have further developed a mathematical model for *determination of the optimum rate of stock removal factor* Q_i (cm^3/min). It works out based on *the total cost of the given operation* K_Σ (HUF) as an *objective function*, taking into consideration *the limit of total machining time* $\sum_{i=1}^{z} t_{m,i} = t_m \leq t_{ml}$ (min) as a *constraint* valid for the operation as a whole. We assume that the dispatcher's time limit t_{ml} related to the total machining time t_m of operation in question is realizable. For example it is based on empiric considerations from the workshop. Determination of optimum stock removal factor in machining processes is very important, because the intensive parameter values (depth of cut, feed rate and cutting speed) are originating from its rate.

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

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

Where:

V_Σ: is the total volume to be removed.

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

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

Discussion:

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

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

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

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

THESIS 3

Considering the optimization problem with regards to fundamentals and principles mentioned previously. I have further developed the mathematical model along with an advantageous numerical solving method of programming.

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

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

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

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

4. The *process needs iteration steps* by computer program, which turns the gradient vector $\psi'(Q_i, \lambda)$ to zero.

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

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

Characteristics and advantages of the new method

- The new method is capable to solve the multidimensional optimization problems in machining processes.
- A numerical solution based on Newton-method (gradient method) has been used to solve the highly non-linear system of equations for $N+1$ unknowns namely the range of stock removal factors Q_i and Lagrange multiplier λ.
- Using Hesse matrix is an advanced solution to convert the highly non-linear system of equations into linear ones.
- As the new method of optimisation is equipped with computer program, then it makes it easy to calculate the range of stock removal factors Q_i and Lagrange multiplier λ using iteration methods. Depending on the number of chains, lengths and number of cuts in a workpiece to be cut, the iteration does not stop till the gradient vector of the function $\psi(Q_i, \lambda)$ does not turn to zero
- Modifying each step of iteration the unknown correction vector S_k has been used for the solution of the system of linear equations $H(X_k)S_k = -\psi'(X_k)$ where $H(X_k)$ Hesse matrix the second derivative of $\psi(Q_i, \lambda)$ and $\psi'(X_k)$ the gradient of function $\psi(Q_i, \lambda)$ are only numbers.
- Application of the computer program gives the chance to use technological parameters along with geometry data as input, which can further be stored and used in-group technology in CAPP system.
- The method is a new and solves sophisticated highly non-linear system of equations of the mathematical model used for optimization problems in cutting conditions.
- The new method is restricted to turning operation, and can be generalized for other cutting processes as well.

6. Applications of the new scientific results

Process Planning System is a very wide area in manufacturing system as it deals with how to manufacture an individual product, being an assembly or a single-part. It aims at manufacturing the considered product in the most cost effective way considering technological constraints and preferences. This area includes: interpretation of the product model, selection of machines, set-ups, tool designing as well as machining methods and machining sequences and NC/CNC programming. At this area there are some types of automated process planning (e.g. the variant method, and generative method which represent the available knowledge and experiences) this kind of automated process planning is called Computer Aided Process Planning (CAPP). In order to apply CAPP in a cost effective way, and to over come the problems arising form the technical and economical aspects, companies usually try to reduce their costs, lead-time and at the meantime increase their productivity. These objectives are not obtained without consideration of optimum use of machines, machine tools and other marginal costs. Considering the optimization problems the new methods applied in this Thesis have resulted in developing of three new results which two of them equipped with two practical programs as well. These three new results can solve some optimisation problems of Computer Aided Process Planning (CAPP) in CIM environment. We can use these new results in order to test whether the workpiece to be cut is cost effective or not. The application of the new method may be as follows:

1. Using the new method we can test the new product plan, before any prototyping process, then the test results can give the chance whether the applied plan for the new product fulfils the decision makers' satisfaction or not.
2. As cost equivalent-time function gives the specific time of the rate of stock removal to the lowest cost, the new method can express technical and economical aspects at the same time.
3. The new method can solve and optimize the multidimensional cutting conditions problems by means of iterations and based on the geometry of the new product and given technological parameters, the most optimum values for the rate of stock removal factors and consequently for time-equivalent cost function are obtained.
4. Based on the new method lots of products plan with different geometry can be tested and stored for the further application or collected to be used in Group Technology (GT) as well.

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

APPENDIX 1.

Database used in the computer programs

Material Group	[1] C10, C15K, C25, A38, A42, 37B, AS1, ASPb					
Res or HB	300 - 500 (N/mm^2)					
Type of tip	Conventional				Coated	
Machining type	Smooth Turning	Semi-Smooth Turning	Rough Turning			
Quality of edge	SB10	SB20	SB30	SB40	R121	R131
Average Tool wear allowed	0.3	0.4	0.5	0.6	0.3	0.5
C_v	398.22	325.49	284.69	246.13	510.76	405.62
y_v	0.30	0.33	0.35	0.38	0.30	0.35
x_v	0.05	0.08	0.09	0.07	0.05	0.10
m	0.20	0.20	0.20	0.20	0.20	0.20
v_{min}	217	159	118	96	278	180
v_{max}	464	305	199	152	596	323
f_{min}	0.1	0.2	0.4	0.6	0.1	0.3
f_{max}	0.4	0.5	0.7	0.9	0.4	0.6
λ_{min}	2.5	4	5	6	2.5	5
λ_{max}	40	25	18	15	40	20

Material Group	[2] C35, A50, Aö52, BNC5, BC1, BC3, CMo1, 52C, Cr3					
Res or HB	500 - 600 (N/mm^2)					
Type of tip	Conventional				Coated	
Machining type	Smooth Turning	Semi-Smooth Turning	Rough Turning			
Quality of edge	SB10	SB20	SB30	SB40	R121	R131
Average tool wear allowed	0.3	0.4	0.5	0.6	0.3	0.5
C_v	364.34	307.36	265.86	249.88	482.56	382.43
y_v	0.30	0.33	0.35	0.35	0.30	0.35
x_v	0.04	0.08	0.09	0.11	0.05	0.10
m	0.20	0.20	0.20	0.20	0.20	0.20
v_{min}	202	151	110	91	263	170
v_{max}	423	290	187	144	562	305
f_{min}	0.1	0.2	0.4	0.6	0.1	0.3
f_{max}	0.4	0.5	0.7	0.9	0.4	0.6
λ_{min}	2.5	4	5	6	2.5	5
λ_{max}	40	25	18	15	40	20

Material Group	[3] C35e, C45, C60K, A60, A70, 55S, CMo1e, CMo3, CMo4, BNC6, M1					
Res. or HB	600 - 700 (N/mm^2)					
Type of tip	Conventional				Coated	
Machining type	Smooth Turning	Semi-Smooth Turning	Rough Turning			
Quality of edge	SB10	SB20	SB30	SB40	R121	R131
Average tool wear allowed	0.3	0.4	0.5	0.6	0.3	0.5
C_v	323.95	267.36	230.93	214.25	387.12	335.93
y_v	0.30	0.33	0.34	0.36	0.31	0.35
x_v	0.05	0.08	0.10	0.10	0.04	0.13
m	0.25	0.25	0.25	0.25	0.25	0.25
v_{min}	144	107	77	65	177	100
v_{max}	330	220	139	110	404	229
f_{min}	0.1	0.2	0.4	0.6	0.1	0.3
f_{max}	0.4	0.5	0.7	0.9	0.4	0.6
λ_{min}	2.5	4	5	6	2.5	6
λ_{max}	40	25	18	15	40	20

Material Group	[4] C45e, C60e, A60e, A70e, MN2, W5, W9, GO3, Cr2e, CMo1e, CMo3e, CMo4e, K4, K13, NCMo5, CrV3					
Res or HB	700 - 900 (N/mm^2)					
Type of tip	Conventional				Coated	
Machining type	Smooth Turning	Semi-Smooth Turning	Rough Turning			
Quality of edge	SB10	SB20	SB30	SB40	R121	R131
Average tool wear allowed	0.3	0.4	0.5	0.6	0.3	0.5
C_v	286.96	238.18	228.31	192.99	397.37	296.44
y_v	0.30	0.33	0.25	0.34	0.28	0.35
x_v	0.05	0.08	0.11	0.10	0.06	0.10
m	0.30	0.30	0.30	0.30	0.30	0.30
v_{min}	103	77	59	46	138	86
v_{max}	254	169	110	85	133	179
f_{min}	0.1	0.2	0.4	0.6	0.1	0.3
f_{max}	0.4	0.5	0.7	0.9	0.4	0.6
λ_{min}	2.5	4	5	6	2.5	5
λ_{max}	40	25	18	15	40	20

Material Group	[5] C60e, DMo5, KLe, K12, NCMo5e, CMo3e, CMo4e, CrV3e					
Res. or HB	900 - 1000 (N/mm^2)					
Type of tip	Conventional				Coated	
Machining type	Smooth Turning	Semi-Smooth Turning	Rough Turning			
Quality of edge	SB10	SB20	SB30	SB40	R121	R131
Average tool wear allowed	0.3	0.4	0.5	0.6	0.3	0.5
C_v	336.33	279.47	247.06	229.24	418.39	342.95
y_v	0.30	0.33	0.33	0.33	0.30	0.35
x_v	0.05	0.08	0.11	0.00	0.04	0.09
m	0.39	0. 39	0. 39	0. 39	0. 39	0. 39
v_{min}	82	61	36	36	104	68
v_{max}	231	155	76	76	290	161
f_{min}	0.1	0.2	0.4	0.6	0.1	0.3
f_{max}	0.4	0.5	0.7	0.9	0.4	0.6
λ_{min}	2.5	4	5	6	2.5	5
λ_{max}	40	25	14	15	40	20

Material Group	[6] Ferritic KO1, KO2, KO3, KO4, KO6					
Res. or HB	450 - 650 (N/mm^2)					
Type of tip	Conventional				Coated	
Machining type	Smooth Turning	Semi-Smooth Turning	Rough Turning			
Quality of edge	EB20	SB20				R131
Average tool wear allowed	0.4	0.4				0.4
C_v	280.75	279.32				357.33
y_v	0.33	0.33				0.35
x_v	0.08	0.08				0.10
m	0.30	0.30				0.30
v_{min}	90	90				113
v_{max}	199	199				260
f_{min}	0.2	0.2				0.2
f_{max}	0.5	0.5				0.5
λ_{min}	4	4				4
λ_{max}	25	25				25

Material Group	[7] Perlitic , martensitic KO11 ,KO12 , KO16					
Res. or HB	500 - 800 (N/mm^2)					
Type of tip	Conventional				Coated	
Machining type	Smooth Turning	Semi-Smooth Turning	Rough Turning			
Quality of edge	EB20	SB20				R131
Average tool wear allowed	0.4	0.4				0.4
C_v	222.78	222.78				315.10
y_v	0.33	0.33				0.35
x_v	0.08	0.08				0.10
m	0.30	0.30				0.30
v_{min}	72	72				100
v_{max}	129	159				229
f_{min}	0.2	0.2				0.2
f_{max}	0.5	0.5				0.5
λ_{min}	4	4				4
λ_{max}	25	25				25

Material Group	[8] Austenitic K2, K11, KO32, KO33, KO34, KO35, KO36, KO39					
Res. or HB	500 - 800 (N/mm^2)					
Type of tip	Conventional				Coated	
Machining type	Smooth Turning	Semi-Smooth Turning	Rough Turning			
Quality of edge	EB20	SB20				R131
Average tool wear allowed	0.4	0.4				0.4
C_v	181.00	152.05				246.97
y_v	0.33	0.44				0.35
x_v	0.08	0.08				0.10
m	0.30	0.30				0.30
v_{min}	58	58				78
v_{max}	129	129				179
f_{min}	0.2	0.2				0.2
f_{max}	0.5	0.5				0.5
λ_{min}	4	4				4
λ_{max}	25	25				25

Material Group	[9] Öv 10 ,Töp 35					
Res. Or HB	2200 (N/mm^2)					
Type of tip	Conventional				Coated	
Machining type	Smooth Turning	Semi-Smooth Turning	Rough Turning			
Quality of edge	HB10	HB20				R11
Average tool wear allowed	0.3	0.5				0.4
C_v	257.02	226.86				345.22
y_v	0.22	0.22				0.22
x_v	0.10	0.13				0.13
m	0.20	0.20				0.20
v_{min}	121	89				205
v_{max}	249	149				269
f_{min}	0.1	0.3				0.2
f_{max}	0.4	0.5				0.5
λ_{min}	2.5	5				4
λ_{max}	40	20				25

Material Group	[10] Öv 15 , Göv 38 , Töp 45					
Res. or HB	1400 - 2200 (N/mm^2)					
Type of tip	Conventional				Coated	
Machining type	Smooth Turning	Semi-Smooth Turning	Rough Turning			
Quality of edge	HB10	HB20				R11
Average tool wear allowed	0.3	0.5				0.4
C_v	197.78	180.94				275.69
y_v	0.22	0.22				0.22
x_v	0.10	0.13				0.13
m	0.20	0.20				0.20
v_{min}	91	71				115
v_{max}	189	120				209
f_{min}	0.1	0.3				0.2
f_{max}	0.4	0.6				0.5
λ_{min}	2.5	5				4
λ_{max}	40	20				25

Material Group	[11] Öv 20, Öv 25, Töp 50, Göv 50					
Res. or HB	1800 - 2600 (N/mm^2)					
Type of tip	Conventional				Coated	
Machining type	Smooth Turning	Semi-Smooth Turning	Rough Turning			
Quality of edge	HB10	HB20				R11
Average tool wear allowed	0.3	0.5				0.4
C_v	115.10	151.01				157.32
y_v	0.22	0.22				0.22
x_v	0.10	0.13				0.13
m	0.20	0.20				0.20
v_{min}	54	59				66
v_{max}	112	99				120
f_{min}	0.1	0.3				0.2
f_{max}	0.4	0.6				0.5
λ_{min}	2.5	5				4
λ_{max}	40	20				25

Material Group	[12] Öv 30 , Töp 70					
Res. or HB	2400 - 2800 (N / mm^2)					
Type of tip	Conventional				Coated	
Machining type	Smooth Turning	Semi-Smooth Turning	Rough Turning			
Quality of edge	HB10	HB20				R11
Average tool wear allowed	0.3	0.5				0.4
C_v	128.14	106.23				170.77
y_v	0.22	0.22				0.22
x_v	0.10	0.13				0.13
m	0.20	0.20				0.20
v_{min}	60	41				71
v_{max}	124	69				130
f_{min}	0.1	0.3				0.1
f_{max}	0.4	0.6				0.5
λ_{min}	2.5	5				4
λ_{max}	40	20				25

Material Group	[13] Öv 35					
Res. or HB	2800 (N/mm^2)					
Type of tip	Conventional				Coated	
Machining type	Smooth Turning	Semi-Smooth Turning	Rough Turning			
Quality of edge	HB10	HB20				R11
Average tool wear allowed	0.3	0.5				0.4
C_v	115.10	151.01				157.32
y_v	0.22	0.22				0.22
x_v	0.10	0.13				0.13
m	0.20	0.20				0.20
v_{min}	54	59				66
v_{max}	112	99				120
f_{min}	0.1	0.3				0.2
f_{max}	0.4	0.6				0.5
λ_{min}	2.5	5				4
λ_{max}	40	20				25

APPENDIX 2

Derivation of mathematical function ψ used for optimization

Derivation of function (7.23) results in *N+1* non-linear system of equations. Let us expand the function as follows:

$$\psi = k\sum_{i=1}^{z}\left(\frac{1}{Q_i}+\frac{Q_i^{q-1}}{R_i^q}\right)V_i + \lambda k\left(\frac{A\sum_{i=1}^{z}\left(\frac{R_i}{Q_i}\right)^q\cdot\left(\frac{V_i}{Q_i}\right)}{\sum_{i=1}^{z}\left(\frac{V_i}{Q_i}\right)} - T_W\right) =$$

$$k\left(\frac{1}{Q_1}+\frac{Q_1^{q-1}}{R_1^q}\right)V_1 + k\left(\frac{1}{Q_2}+\frac{Q_2^{q-1}}{R_2^q}\right)V_2 + k\left(\frac{1}{Q_3}+\frac{Q_3^{q-1}}{R_3^q}\right)V_3 + \ldots\ldots\ldots\ldots + k\left(\frac{1}{Q_i}+\frac{Q_z^{q-1}}{R_z^q}\right)V_z +$$

$$+\lambda k\left[\frac{A\left[\left(\frac{R_1}{Q_1}\right)^q\cdot\left(\frac{V_1}{Q_1}\right)+\left(\frac{R_2}{Q_2}\right)^q\cdot\left(\frac{V_2}{Q_2}\right)+\left(\frac{R_3}{Q_3}\right)^q\cdot\left(\frac{V_3}{Q_3}\right)+\ldots\ldots\ldots\ldots\ldots+\left(\frac{R_z}{Q_z}\right)^q\cdot\left(\frac{V_z}{Q_z}\right)\right]}{\left(\frac{V_1}{Q_1}+\frac{V_2}{Q_2}+\frac{V_3}{Q_3}+\ldots\ldots\ldots+\frac{V_z}{Q_z}\right)} - T_W\right]$$

Notations:

$$\frac{V_1}{Q_1}+\frac{V_2}{Q_2}+\frac{V_3}{Q_3}+\ldots\ldots\ldots+\frac{V_z}{Q_z} = D = D(Q_1,Q_2,Q_3,\ldots\ldots,Q_z)$$

$$\left(\frac{R_1}{Q_1}\right)^q\cdot\left(\frac{V_1}{Q_1}\right)+\left(\frac{R_2}{Q_2}\right)^q\cdot\left(\frac{V_2}{Q_2}\right)+\left(\frac{R_3}{Q_3}\right)^q\cdot\left(\frac{V_3}{Q_3}\right)+\ldots\ldots\ldots\ldots\ldots+\left(\frac{R_z}{Q_z}\right)^q\cdot\left(\frac{V_z}{Q_z}\right) = u = u(Q_1,Q_2,Q_3,\ldots\ldots,Q_z)$$

Now we derivate function (7.23) with respect to Q_1, Q_2, Q_3,………and Q_z as follows:

$$\frac{\partial \psi}{\partial Q_1} = k\left(-\frac{V_1}{Q_1^2} + \frac{q-1}{R_1^q} Q_1^{q-2} V_1\right) + A\lambda k \frac{R_1^q V_1 \left(-(q+1)\right) . \frac{1}{Q_1^{q+2}} . D + u . \frac{V_1}{Q_1^2}}{D^2} = 0.$$

$$\frac{\partial \psi}{\partial Q_2} = k\left(-\frac{V_2}{Q_2^2} + \frac{q-1}{R_2^q} Q_2^{q-2} V_2\right) + A\lambda k \frac{R_2^q V_2 \left(-(q+1)\right) . \frac{1}{Q_2^{q+2}} . D + u . \frac{V_2}{Q_2^2}}{D^2} = 0.$$

$$\frac{\partial \psi}{\partial Q_3} = k\left(-\frac{V_3}{Q_3^2} + \frac{q-1}{R_3^q} Q_3^{q-2} V_3\right) + A\lambda k \frac{R_3^q V_3 \left(-(q+1)\right) . \frac{1}{Q_3^{q+2}} . D + u . \frac{V_3}{Q_3^2}}{D^2} = 0.$$

.

$$\frac{\partial \psi}{\partial Q_z} = k\left(-\frac{V_z}{Q_z^2} + \frac{q-1}{R_z^q} Q_z^{q-2}\right) + A\lambda k \frac{R_z^q V_z \left(-(q+1)\right) \frac{1}{Q_z^{q+2}} . D + u . \frac{V_z}{Q_z^2}}{D^2} = 0.$$

The best way to solve such a non-linear systems of equation is a numerical method. The method of solution was explained at section 7.3 of CHAPTER 7.

APPENDIX 3

Algorithm for solving Q_i and λ

The main idea of the method is as follows:

Let us denote the derivation of function $\psi(Q_i,\lambda)$ with its gradient vector $\psi'(Q_i,\lambda)$. The aim is to solve the non-linear system of equations to find Q_i and λ, so that, the gradient vector $\psi'(Q_i,\lambda)$ of function $\psi(Q_i,\lambda)$ should turn to zero as follows:

$$\frac{\partial \psi}{\partial Q_1} = \psi'(Q_1, \lambda) = 0.$$

$$\frac{\partial \psi}{\partial Q_2} = \psi'(Q_2, \lambda) = 0.$$

$$\frac{\partial \psi}{\partial Q_3} = \psi'(Q_3, \lambda) = 0.$$

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$$\frac{\partial \psi}{\partial Q_i} = \psi'(Q_z, \lambda) = 0.$$

Let us denote the *k-th* iteration in the method of solution (numerical method of solution) with X_k for range of the values for Q_i and λ.

We start the first step of the method from X_0 where $X_0 = (Q_1 = Q_2 = Q_3 = \quad Q_z = 200, \lambda = 1.3)$.

These values of x_0 were chosen from practical observations. In each step we modify X_k by S_k obtaining $X_{k+1} = X_k + S_k$ (for example in case $k = 0$, then $X_1 = X_0 + S_k$), where S_k is the vector obtained as a solution in each step from a system of *linear equations* as follows:

$$H(X_k).S_k = -\psi'(X_k)$$

$$\begin{pmatrix} & & \\ & & \\ & \text{Symmetric Hesse Matrix} & \\ & & \\ & & \end{pmatrix} \begin{pmatrix} S_1 \\ S_2 \\ S_3 \\ \\ \\ \\ S_n \end{pmatrix} = - \begin{pmatrix} \psi'_1 \\ \psi'_2 \\ \psi'_3 \\ . \\ . \\ . \\ \psi'_z \end{pmatrix}$$

Where $H(X_k)$ is called Hesse matrix of the function $\psi(Q_i, \lambda)$ and as previously mentioned S_k is the vector. This matrix is constructed from the second derivative $H(X_k) = \frac{\partial^2 \psi}{\partial X_i \partial X_j}$ of function $\psi(Q_i, \lambda)$ and the second derivatives in Hesse matrix were computed numerically in the program. The method converges not too fast.