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Wrocław University of Technology

Production Management

Józef Krzyżanowski

# FLEXIBLE MANUFACTURING TECHNOLOGY

## Flexible Manufacturing Automation

Wrocław 2011

Projekt współfinansowany ze środków Unii Europejskiej w ramach
Europejskiego Funduszu Społecznego

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CONTENTS

# 1. INTRODUCTION

The flexible automation in manufacturing is a stage in the development of production technology associated mainly with the inclusion of the domain of transferring technical and economic information to the production automation process. Hence, the term “flexible manufacturing system” (FMS) should first of all mean certain concept of automated manufacturing with the use of informatics technology. The FMS is not a new production installation; its substance is the integration of a range of various installations to realize the concept in practice. As William W. Luggen [29] says, the concept of flexible manufacturing system was born in London in the sixties of last century. David Williamson, who was also the inventor of the trade name “Flexible Machining System”, formulated it. The shortened name FMS has been quickly accepted in the technical circles, and although its abbreviated name FMS remained the same, because of broadened use became known as Flexible Manufacturing System.

The first system, according to Williamson’s concept that was installed in the industry, was named System 24 (or Molins 24), because it was designed to work 24 hours per day, including 16 hours of unmanned manufacturing. This was possible thanks to the use of a computer control. Work pieces would be loaded manually on the pallets, which would then be delivered to NC machines and loaded automatically when needed. Each machine would be equipped with a store, from which tools could be selected systematically to perform a variety of different operations. Included in this overall process were systems for removing chips and cleaning the work pieces. This system has combined the versatility of NC machines with a low manning level.

The users of the first FMS have quickly noticed that the basis of functioning of them predestinates it to automated manufacturing products of great versatility, with a low production range. Further development of this concept was associated with a necessity to introduce to the system of monitoring and diagnosis of its operation. This became a reality, when in the seventies followed a stormy development of control systems and computer technology - personal computer appeared. One feature to characterize the present period of FMS development is the broadening of the range of the flexible automation onto other technology of manufacturing: for example forming, electro machining, or assembly.

What is a Flexible Manufacturing System? It is difficult to define a synonymous answer to such a question in a form of generally accepted definition. It markedly depends on an accepted point of view. William W. Luggen in his book “Flexible Manufacturing Cells and Systems” [29] presents six definitions of FMS which can be found in the US government publications.

1. FMS is a series of automatic machine tools or items of fabrication equipment linked together with an automatic material handling system, a common hierarchial digital preprogrammed computer control, provision random fabrication of parts or assemblies that fall within predetermined families. (United States Government definition).
2. A FMS is a group of NC machine tools, which can randomly process a group of parts, having automated material handling equipment and central computer control to dynamically balance resource utilization so, that the systems can be adapt automatically to changes in parts production, mixes, and levels of output. (Definition used by Kearney and Trecker Co.).
3. FMS is a randomly loaded automated system based on group technology manufacturing linking integrated computer control and a group of machines to automatically produce and handle (move) parts for continuous serial processing.
4. FMS combines microelectronics and mechanical engineering to bring the economics of scale to batch work. A central on-line computer controls the machine tools, other workstations, and the transfer of components and tooling. The computer also provides monitoring and information control. This combination of flexibility and overall control makes possible the production of a wide range of products in small numbers.
5. FMS is a process under control to produce varieties of components or products within its stated capability and to a predetermined schedule.
6. FMS is a technology, which enables to achieve leaner factory facilities with better response times, lower unit costs and higher quality under an improved level of management and central control.

As we can see, the above listed definitions are varying widely, and each of them would emphasize another aspect of the FMS. The first definition reflects the best way its substance, from the project designer and the user of the system, and it is the basis for the consideration in this paper.

All above introduced basic definitions repeatedly use such expressions as “NC machine tools, automatic material handling, central computer control, linked together, and flexible”. Explanation of these concepts and broader description thereof should then bring nearer the answer to the basic question – What is the “flexible manufacturing system”. Discussion on a particular question cannot depend on dividing the whole entity to particles and describing each of them separately, but rather on considering the particular question in the context of the system as a whole. Having this in mind and before proceeding to describe a problem associated with the structure and functioning of FMS, one should define the “system” in general and the “manufacturing system” in particular.

Both general and precise definition of the "system" meets similar difficulties as in defining the "flexible manufacturing system" due to the same reasons. In the frame of general theory of systems, there have been formulated many definitions of this notion. Having in view to turn to the "manufacturing systems", the most appropriate one seems to be the following: *The system S is a given set of elements, and their constant behavior, as well as a set of connections among the elements and between the elements and the surroundings.*

The basic system approach is a still actual Aristotelian contention that *the whole is more than the sum of parts*.

In the course of the scientific revolution in XVI-XVII centuries, certain approach was accepted, which unfortunately in many cases lingers in the science until to-day and is called "mechanistic materialism". Descartes formulated one of the main bases of this approach as follows: *each problem should be disrupted on so many separated simple elements as much as it is possible*. This is a paradigm of modern science from a time of its origin until contemporary experimental investigations. It is based on the reduction of a complex cases and their disintegration into elements. This method resulted in a great success in the science and technologies; however, it functioned well only when observed occurrences could be divided onto isolated causal chains that means into relations, which occurred between two or more variables.

However, this situation became inconvenient when the questions of many variables were discussed (many "ins" and "outs" in a system). The mechanistic approach did not show any possibility to explain the basic question for the functioning of a complex system.

The solution came with the "system approach" in relation to Aristotle's contention and with assumption that the order of the organization of certain whole system does exceed beyond their parts when considered in reciprocal isolation. This fact can be stated empirically, in a course of investigations carried in different remotely placed spheres, having to do with for e.g. living organisms, social groups, or structures of an atom.

At the end of the 1920-s, one of the originators of the general theory of systems, Ludwig von Bertalanffy wrote [3]: *Since the basic feature of the organized whole is just its organization, the traditional methods of investigation and description of particular elements and proceedings cannot give a full explanation of occurrences of functioning this whole. They do not give namely any information about the coordination of particular parts and proceedings. In addition, therefore the main task must be exerted in discovering the regulations, which rule the systems on all levels of their organization*. One should add, that by using the term "the organized whole", the author has in mind everything: the living being, the social group, personality, as well as the technical installation. The above statement can be concisely produced as follow: to understand the functioning of the organized whole, we must know both: their parts as well as relations between themselves. Using the terminology of the theory of the systems, the structure of the system is defined as the kind, the number and the properties of its elements as well as the quantitative and qualitative relations between themselves. (Fig. 1.1).

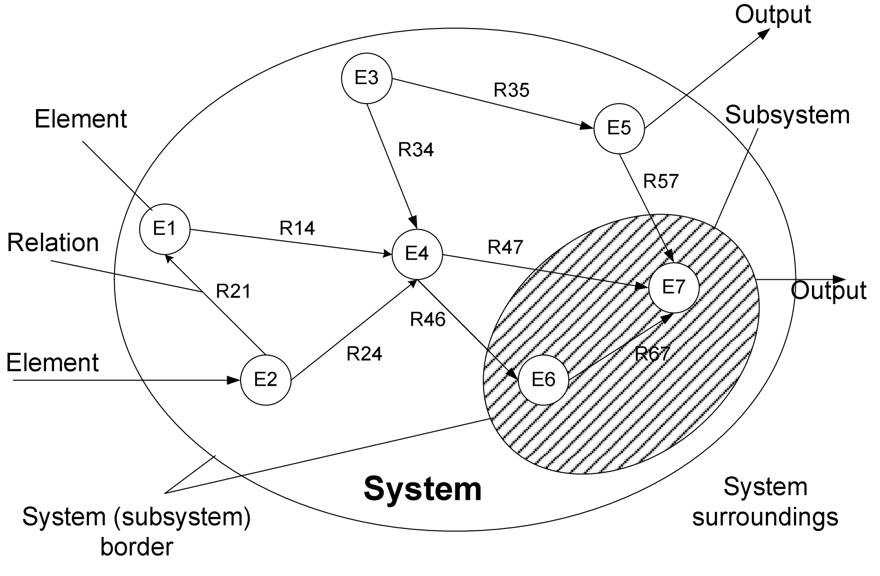



Fig. 1.1. Structure of the system

Accepting the definitions, made with respect to the general notion of a system, one can in turn undertake an effort to define what the *manufacturing system* is.

According to the accepted definition, each system is a part conventionally isolated of a certain (in general case, unlimited), whole. Thus, a system is always located in a defined surroundings. The basic question met when trying to imply a system approach, is to define the limits of a system under consideration. When selecting thereof, such features should be taken in consideration as the usefulness, range, univocal nature, wholeness, generality. The extended systems may be divided into such sub-systems, which than may be taken in consideration, usually from a different point of view, as separate systems. Such sub-system may be characterized quite different and formally described in quite a different way. An example of multi aspect complex system is a production enterprise together with its surroundings.

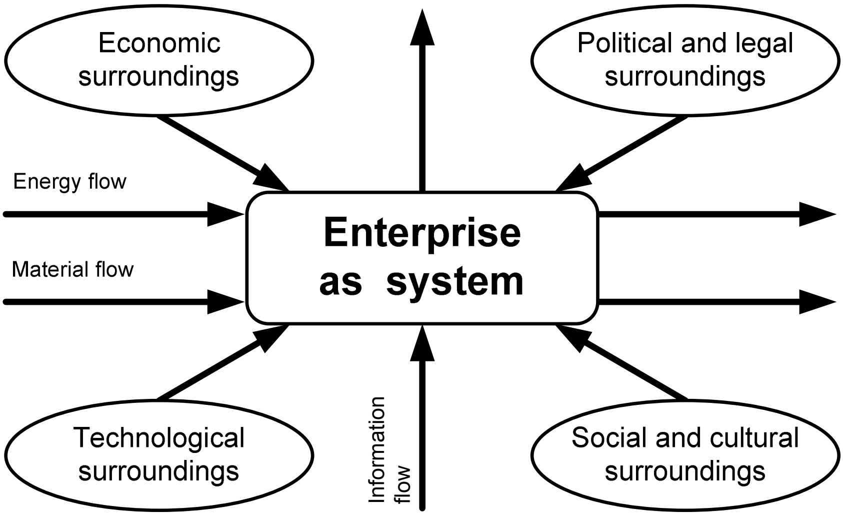



Fig. 1.2. Surroundings of a system "enterprise"

To undertake a decision concerning the functioning of a system "enterprise" as a whole, the entire surroundings must be taken in consideration, including the relation between them and the enterprise. When considering the technical question of manufacturing, there should be, however, an isolated subsystem in the frame of an enterprise, which will be named a *manufacturing system*. It can be defined in a following way:

*The manufacturing system is a substantial informational and organizational structure aimed to manufacture define products.*

The idea of a manufacturing system corresponding to it's present understanding has been introduced in the second half of the sixties in 1967, by Gunter Spur [46]. Although he did this with reference to a machine tool (Fig. 1.3), he developed the system concept of a machine tool in 1972 and published in his book "Optimierung des Fertigungssystems Werkzeugmaschine" [47]. As a basic transformation in this system, Spur considers the transformation of a semi-product (the machined work piece), into ready-made product (finished product). The joint operation of all components of a machine tool is defined as a "function". Therefore, the limits of a subsystem in the manufacturing system are in the most useful way determined according to spheres of functioning. In the circle of a machine tool, five spheres of functioning are selected focusing all necessary functions to sufficiently operate a manufacturing process:

1. Work piece system
2. Tooling system
3. Kinematics system
4. Energetic system
5. Information system

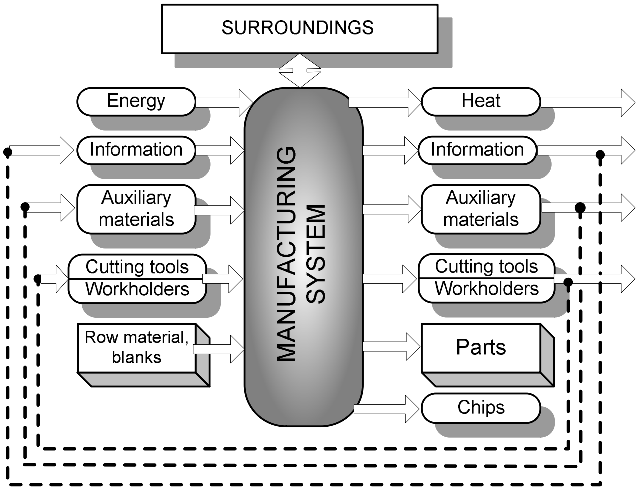



Fig. 1.3. Block diagram of a machine tool as manufacturing system according to G.Spur [46]

One should have in mind that the limits of the defined subsystem do not reflect the division of its material structure. The same elements or assemblies of a machine tool can carry out the functions in conjunctions to several spheres of functioning.

The substance of a manufacturing process, as it is shown in the schematic diagram (Fig.1.3), is the flow of the material and energetic streams. During the flow through the system, the components of these streams are subjected to transformation.

The material stream on the entry to the system consists of semi-products, tools and liquids suitable to be used as well as exploitations materials. On the way out, the stream consists of ready-made products, partly or completely worn-out tools, contaminated and used coolant, waste products and chips. Similarly, the information stream at its entry contains the following: information about the manufacturing process of particular pieces, NC programs on particular machine tools, possible NC programs for other installations, information about setting tools and conditions of cutting edges. On the exit, the part of information remains unchanged, and part (for example concerning tools) is actualized.

All functions realized in manufacturing require the expenditure of energy that was expressed as the transfer of energy flow. The system is actually fed from electric installation and from the control installation of compressed air. The flow of energy at the exit becomes then the heat and the air decompressed to a level of atmospheric pressure. The energy systems (ES) do not differ in principle from the supply networks in conventional manufacturing and therefore will be not broadly discussed. The manufacturing systems of variable complexity differ in the range of the realized functions by particular existing subsystems. It often involves the necessity to separate them, to make the description more transparent of subsequent subsystems of a lower range.

# 2. NEED FOR FLEXIBLE MANUFACTURING SYSTEMS

The process of manufacturing technology development is a result of simultaneous affecting of technical possibilities given by the current technological conditions in the industry, as well as of the market demands. Both spheres are not independent but significantly coupled. This process is besides stimulated by economic calculation.

This statement can by formulated as follows:

*The technical possibilities are a set of necessary conditions whereas market demands and economic calculation form a set of conditions sufficient for ensue a qualitative change in process of manufacturing technology development.*

One of the most important conditions necessary to develop and realize the concept of flexible automation manufacturing, was the existence of NC manufacturing installations, and first of all, the NC machine tools. The process of using them in the industrial practice illustrates well the still existing difficulties with the introduction of FMS. The introduction of numerical control in the machine tools industry happened approximately between 1965 and 1975. Broader use of the numerically controlled machines (it e. NC) came slowly, and was met with a great resistance. The main reasons were rooted in the economic conditions. These machine tools were in the beginning relatively expensive in comparison to the conventional ones. The costs of a machine tool were elevated by the costs of their control systems, programming and training of the personnel. The reliability of these machine tools and first of all their systems of control were often not dependable. Programming was time consuming and expensive, therefore servicing and utilization brought new elements quite unfamiliar to personnel trained to operate conventional machine tools, often causing passive resistance. With the time passing, prices of NC machines were systematically lowered. Workers and other personnel became familiar with the FMS. Advantages of these machines became reality, showing effectively, that their purchase presented no more risk from the technical and economic point of view.

Introduction of the computer technology of design and manufacturing, CAD/CAM, met with similar problems of resistance when used with FMS. We should consider that in this case as a rule, we deal with systems much more complicated and expensive, which meant more risk for the manufacturer.

The assumptions accepted to design modern manufacturing installation underwent in the last decades far-going changes. They were conditioned both by the evolution of the market reflecting the state of the world economy, as well as by their development combined with the advance of the technology. The progress of this alteration in the second half of the XX-th century is shown in simplified form in

Fig. 2.1. According to H.Kief [24], five phases in the progress can be distinguished corresponding approximately to a particular decade.

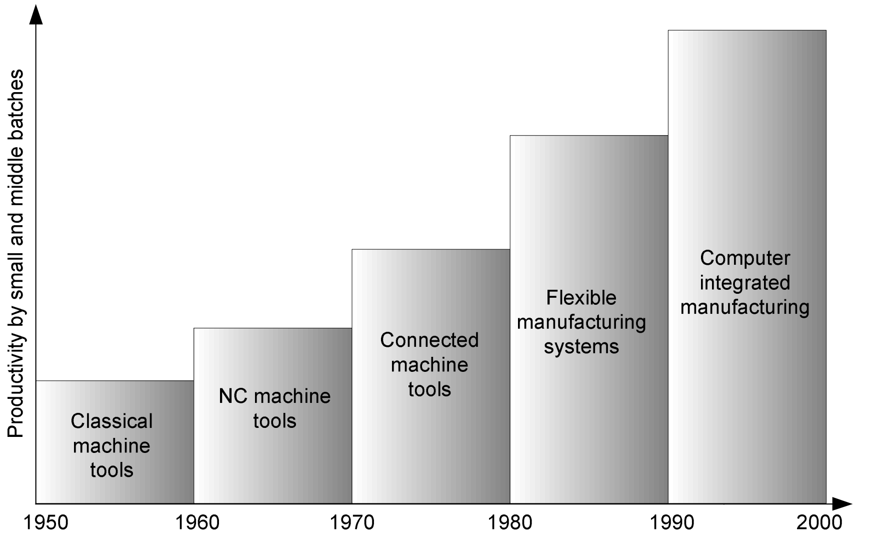



Fig. 2.1. Phases of development of means of production in the second half of XX century

The first phase covering the decade of 1950-1960, is the period of development of production of the conventional machine tools. They had to replace the machinery destroyed in many countries because of war operations (or dismantled) in the aggressor countries in the frame of the war reparations, as in Germany. Following the war damages, the demand for all industrial products was significant. The impoverishment of populations resulting from the war, in countries of Europe and Asia caused in effect, that products were purchased to use them in relatively long period. Therefore, the producer had to assume, that the period of use of the product should be appropriately long. In the industry of machine tools, there was a trend to produce automatic machine tools, to make long series of products. Batch production was rather not in question.

The second phase in the years of 1960-1970 was an animated period in all developed countries. The increased demand created the tendency to modernize the industry and to rationalize production. New generation of machine tools, more precise and efficient, replaced the old machines. Numerically controlled (NC) machine tools appeared in the engineering, requested mainly by the aviation industry, which at the same time intended to introduce a new generation of aircrafts.

The beginning of the third phase, which covers the years 1970-1980, marked the stagnation in the world economy, causing recession in many industrial branches, excessively curbing research and development.
The hitherto existing market of producers changes into market of customers. The main tendencies, which appeared in the industry, are shown, in Fig. 2.2.

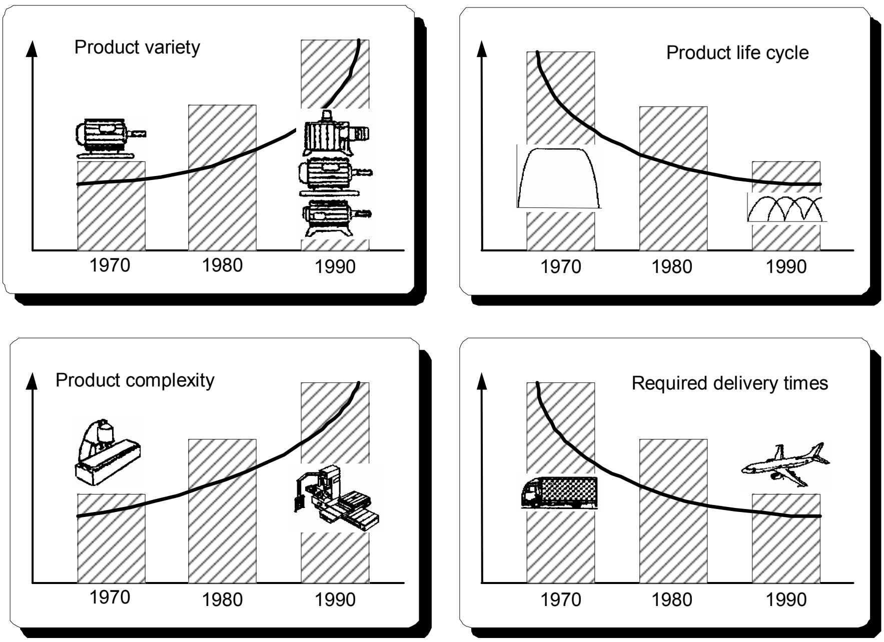



Fig. 2.2. Market trends stimulating the development of flexible manufacturing

In short, the result was that the length of produced batches and the life time of a product were shortened, whereas their variety and the degree of complexity was increased as an effect of a tendency to better satisfy the needs of a client. In these circumstances, the utilization of existing machine tools in good technical conditions became unequal. Some machine tools were only partly used while others were overloaded. In the first place, there was a problem to find flexible solution allowing quick change of both the type of the production and the client's requests. The numerical control (NC) gave the perspective of such a solution. The use of the single NC machine tools did not allow solving all appearing problems connected mainly with the coordination of load of the manufacturing equipment and the means of transport. *"Hence, there arouse necessary conditions to qualitative change of manufacturing technology"*.

In the United States, there appeared some concepts worked out for manufacturing systems in medium and short series production. Based on direct control, they used one computer and several combined NC machine tools. (Concept of DNC – Direct Numerical Control). This idea leads to fourth phase in the decade of 1980 – 1990. The still increasing market requested the flexibility and production efficiency. This puts on the first place the problem of coordinating the activity of different manufacturing equipment and functional sphere of manufacturing system, for example NC machine tools, setting tools equipment, tools store, transport means etc. It became quickly evident, that there is a need for comprehensive solution of the problem of "integrated manufacturing" (CIM), which appear in the fifth phase of development in the beginning of the 1990-s. In the first two phases of development, the actions aimed at rationalizing the production were concentrated on the shortening of main times and on the increase of their part in general time of making the product through shortening of auxiliary times. This was achieved through the following:

- Improving the cutting ability of tools and thus increasing the machining efficiency; for example, applying of ceramic tool insert,
- Increasing the power of machine tools,
- Automation of tool change,
- Inventing multiple tool heads and several supports,
- Automation of part change.

These operations can be than related to shortening the time of realization of the basic functions in the process of machining a workpiece. Example, for conventional manufacturing, of breakdown of available time in a calendar year to a manufacturing operation is shown on the Fig. 2.3.

Similar studies indicate that in a typical manufacturing operation a part moving through a metal-cutting operation would be on an individual machine tool only 5 percent of total time in manufacturing, as depicted in Fig. 2.4. And, when a part is on a particular metal-cutting machine tool, only 1,5 to 2 percent of the part's total manufacturing time is a cutter in the work, actually performing work and adding value. The other 95 percent of the time the part is either moving through the shop or waiting in queue for the next operation.

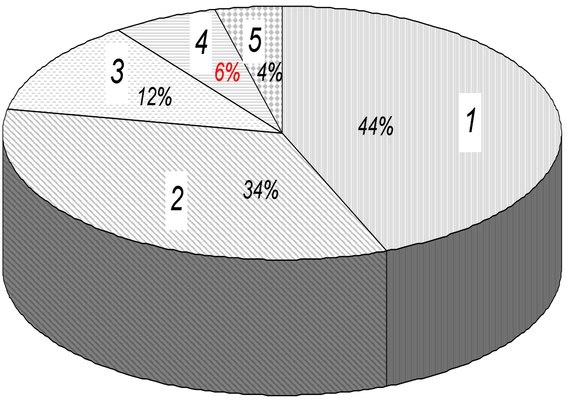



Fig.2.3. Breakdown of 8760 available hours in a calendar year to a manufacturing operation: *1* - inefficient use of second and third shifts, *2* - weekends, holidays, and vacations, *3* - machine and work setup, *4* - **machining**, *5* - unforeseen problems

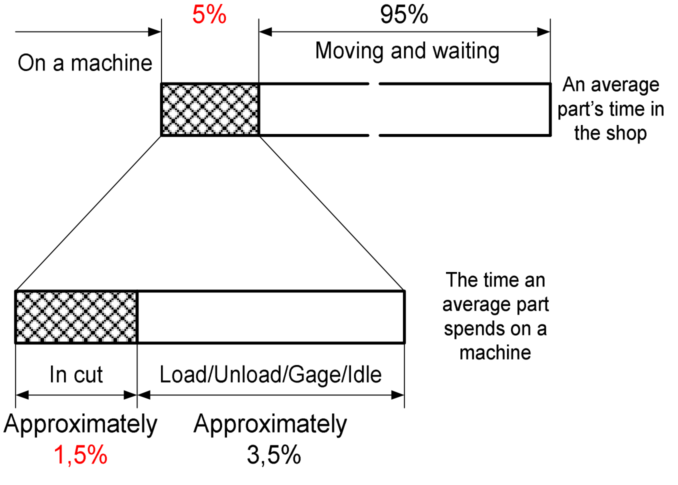



Fig. 2.4. Breakdown of the time spent by an average part in the shop

On theses areas should be found the time reserves bringing the major economic effect. Primarily, there are following subjects under consideration in phases three and four:

- Shifting the tool exchange time to the main time (realization of tool exchanging during the machining time),

- Reducing the waiting time of machine tool (for example for changing the tool, etc.),
- Reducing of standstill times,
- Changing the NC program without stopping the operation,
- Automation of tool management and tool delivery to the machine,
- Automation of tool data transfer from the preset area, after automatic tool gauging, into the FMS tool system database and then to the MCU.

All actions for automation the operation of the system simultaneously fulfill the main requirements in enabling the reduction of the unproductive times of machining tools:

- Working unmanned during the night hours and holidays,
- Working during shift breaks,
- Minimizing the personnel during the third shift.

These trends were resulting not only from the will to increase the efficiency, but were primarily dictated by the cost of highly automated manufacturing system, thus connecting the unproductive standstill to big losses, causing prolonged amortization time.

Under the conditions of buyers market, the possibilities of realization of the described actions may be insured only by the flexible manufacturing automation.

As previously stated, the flexible manufacturing system is not a new particular type of manufacturing equipment, neither is its principle. Its essence is to use the existing NC and automated equipment in such a way as to improve economically profitable medium and short series production on the principle of a group technology and automation of a transfer and conversion the information used in manufacturing process, including the central control if that process. The main feature of a manufacturing system based on these principles is this flexibility. It cannot be univocally defined. One cans distinguish ten aspects of manufacturing system flexibility:

1. *Machine flexibility*
   Various operations performed without set-up change
2. *Material handling flexibility*
   Number of used paths per total number of possible paths between all machines
3. *Operation flexibility*
   Number of different processing plans available for part fabrication
4. *Process flexibility*
   Set of part types that can be produced without major set-up changes, i.e. part-mix flexibility
5. *Product flexibility*
   Ease (time and cost) of introducing products into existing product mix

6. *Routing flexibility*
   Number of feasible routes of all part types/Number of part types
7. *Volume flexibility*
   The ability to vary production volume profitably within production capacity
8. *Expansion flexibility*
   Easy (effort and cost) of augmenting capacity and/or capability, when needed, trough physical changes to the system,
9. *Control program flexibility*
   The ability of a system to run virtually uninterrupted (e.g. during the second and third shifts) due to the availability of intelligent machines and system control software,
10. *Production flexibility*
    Number of all part types that can be produced without adding major capital equipment

Before making a decision regarding investment, while installing a flexible manufacturing system, it should be determined which flexibility aspect is most significant. It will be a deciding factor pertaining to the details of the project. The flexibility of each system is always limited. In case of the flexible manufacturing system the limitations are usually referred to the following cases:

- Defined limited spectrum of parts,
- Limited effectiveness, e.g. by the number of parts produced within the unit of time,
- Limited range of a possible machining operation,
- Limited range of machining accuracy.

Completing all machining parts within the considered spectrum is often not profitable. In such a case, the workpieces must be excluded from the system to make certain operations on other stands. They can be returned to the system, as in the example of the operation of heat treatment made in the central heat treatment department. Only than we can discuss the completeness of manufacturing process realized in the system. The grade of completeness may be quantitatively defined in two ways:

1. Number of operations possible to be realized in the system in relation to the whole number of operations necessary to complete the machining of the workpiece; or in case of differences in time of realization of various operations;
2. As a relation of the sum of duration of the operations realized in the system, to the whole time necessary to complete machining of workpiece.

The grade of completion is a number within the range from 0 to 1.

All limitations of system flexibility should already be exactly defined during their planning phase, due to the severity of economic consequences of faulty assumptions. One of the main reasons of development of automated manufacturing systems was a tendency to take advantage of various type of unproductive time (Fig. 2.3.). To achieve this target within automation of a manufacturing process, a person did a shift changeover. (Figs. 2.5, 2.6, 2.7).

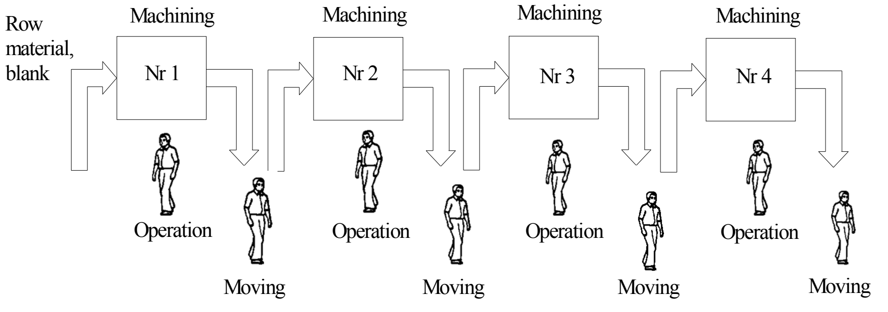



Fig. 2.5. Placing of person in conventional manufacturing process

If this process is considered as the course of events being used to realize definite functions, it may be stated, that the automation thereof is connected with a fact, that a man does withdraw himself from direct realization of these functions, but undertakes the task of programming and supervision. It indicates a physical relief and accepting mental and physical burden instead. Works made in the course of realization the manufacturing process take over the more creative character. In the conventional manufacturing, a man operating all manufacturing equipment and transport means determines to marked degree the rate of running the manufacturing process.

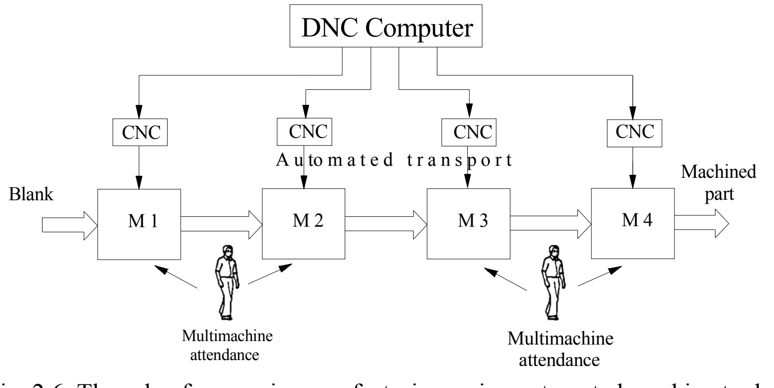



Fig. 2.6. The role of person in manufacturing, using automated machine tools

In an automated manufacturing, using numerically controlled machine tools or machining centers, a man fulfills functions, which are not directly connected with the realization of machining process (Fig. 2.6). He fulfills such functions as changing the workpieces, watching the running process etc. Being relieved from the necessity of directly controlling the machine tool it allows him to manage servicing several machine tools simultaneously. In a flexibly automated manufacturing system, a man is beyond the range of realization of the manufacturing process, as he/she is limited to supervising the results of working system, making corrections if necessary. (Fig. 2.7).

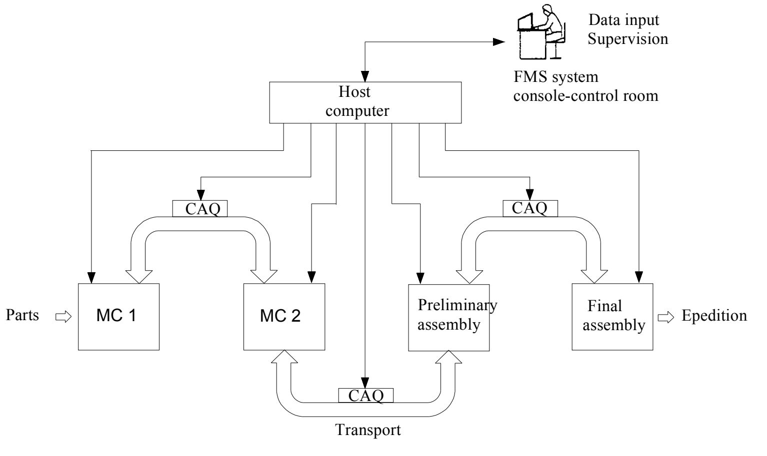



Fig. 2.7. The role of person in flexibly automated manufacturing

Automation of a manufacturing process does not mean elimination of a man from the process. The range of his activity in the process is changing. One should not expect, though, that automation would bring a radical diminishing of work force. This anxiety is accompanied the development of industrial production from the very beginning. In the XVII century in England, for example, the weaving machines were destroyed; in France, all workers being afraid to loose their jobs also destroyed sewing machines during the era of Napoleonic wars –. However, the progress in the machining tools proved them wrong. Since the industrial revolution, despite the periodical labor fluctuation, the numbers of work force had been increasing. The development in the area of industrial production generates new needs, which had not been known in the earlier stages, and reflects changes within flexible automation of manufacturing. Therefore, the service-free working of the system is possible only in a definite period and it requires taking numerous preliminary actions; those are often different with respect to works made in the course of conventional manufacturing process.

# 3. ORGANIZATIONAL CATEGORIES OF FLEXIBLE MANUFACTURING

Every producer tends to gain a maximum profit out of manufactured products. For the achievement of purpose indispensable condition, in an unmonopolistic situation, is the market competitiveness. The most important element of competitiveness, at comparable utilitarian values of products produced by different producers, is the price. Therefore, one of the reason of manufacturing technology development is the trend for sinking the manufacturing costs. Possibility of their determining depends on four fundamental factors characterizing production:

- Production volume (batch number),
- Production capacity,
- Product variety,
- Manufacturing flexibility.

On these factors depends effective utilization of individual organizational form of production.

Fig. 3.1. presents a visually simplified range of economically used various organizational concepts of manufacturing, dependant on the above factors.

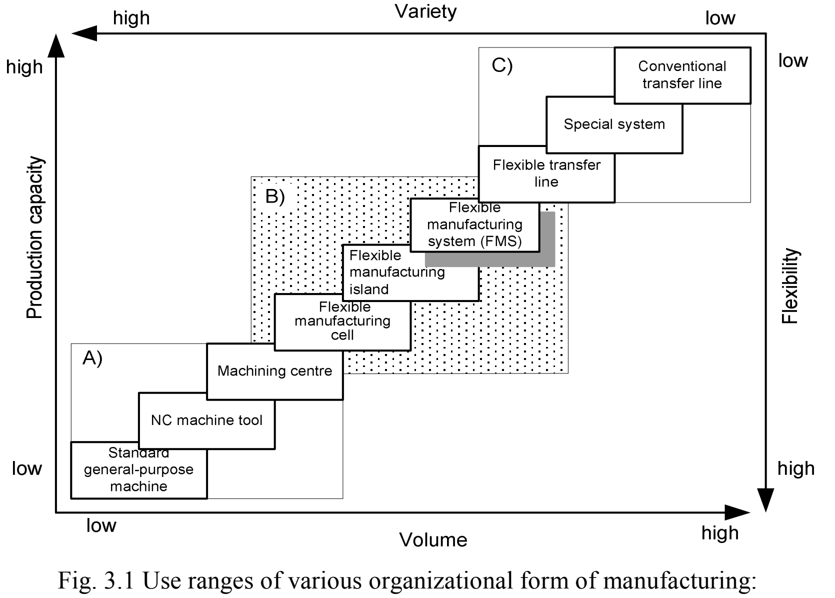



Fig. 3.1 Use ranges of various organizational form of manufacturing:
A) Conventional manufacturing, B) Flexible manufacturing, C) Stiff manufacturing automation

These concepts can be generally divided into three groups:

A – Manufacturing based on independent operation of single machine tools (and other manufacturing equipment); they are featured by a very high flexibility, with the possibility of great variety of produced parts. The least effective way of production; the unit part and small batches production is the economically effective range of use.

B – Flexible and automated production; its featured by relatively great flexibility with comparatively great effectiveness of production with relatively wide spectrum of products. Its range of use is the production of various products in small and medium size series. The market tendencies are in favour of extension of its production range.

C – Highly effective manufacturing, based on the use of special purpose machine tools and production lines: it is featured by a great rigidity in production, principally of one kind of products. Resetting the system for another product is very expensive and time-consuming. This is a most effective way of organizing production. Its effective range of use is a large-lot and mass-production.

From among these groups, having in view the need of flexible automation, the matters of particular interest is the group B which have included the fallowing concepts of manufacturing:

1. Machining centers,
2. Manufacturing cells,
3. Flexible manufacturing islands,
4. Flexible manufacturing systems,
5. Flexible production lines.

The herein presented division is of markedly conventional nature.

*Machining center* (Fig. 3.2.) is a numerically controlled machine tool of high automation degree. It has at least 3 NC axes (translatory motion) and often additionally one or two NC rotary axes. The first machining centers were designed with the destination to work with rotary tools. Therefore, under this denomination and without additional defining they are accepted as the milling machine centers. They are prepared to suit many various machining operations like drilling, milling, boring, threading, or reaming. They possess appropriately wide range of rotational speeds and feeds, and are equipped with great capacity tool magazines (60 to 120 tools) and automatic tool changers. To shorten the auxiliary times they may be provided with automatic pallet changer, whereas fixing and releasing the machined workpieces is made manually within the duration of machining.

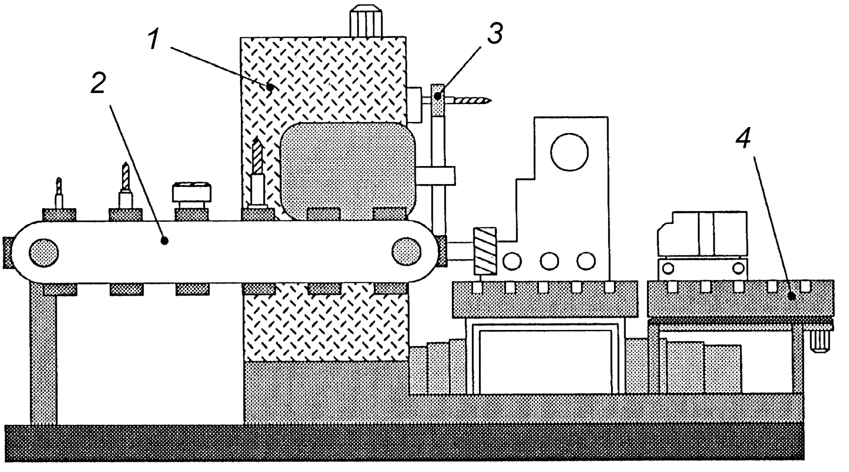



Fig. 3.2. Functional structure of a machining center: *1* – machine tool, *2* – tool matrix, *3* – tool changer, *4* – pallet shuttle

Machining centers are classified as vertical, horizontal (acc. to situation of spindle axis), column (with movable column), and gantry (with steady or movable gantry).

*Manufacturing cell* (Fig. 3.3) is a machining centre with broadened range of automation, enabling unmanned operation of a limited part inventory. Part changing is running automatically until inventory is finished. The required capacity of part store depends first on the machining time of one workpiece. In case of fixing it on a pallet, the whole operation of machining should be about 30 min. In this way, 16 pallets will be enough to ensure work during 8 hours of unmanned shift. Loading and unloading pallets used during the unmanned shift is made usually manually during the shift changing. In case when the work pieces are delivered on the machine tool without pallets, there appears a tendency not to exceed the machined time by more than 3 minutes. For 8 hours duration of unmanned shift one should have about 160 parts on stock. Manufacturing cells are provided with integrated program of installations to carry out monitoring of machining operations and supervising thereof; this refers to the condition of tools in order to change them in case of worn out state, or damage, as well as the machining process with the aim to protect the whole system.

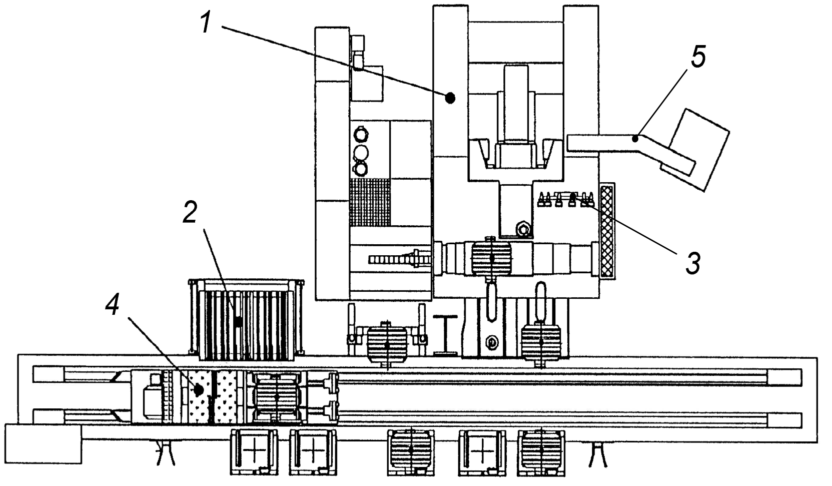



Fig. 3.3. Functional structure of a manufacturing cell: *1* – machining center, 2 – automatic work changer, *3* – tool matrix, *4* – automated pallet movement system, *5* – chip disposal system

Manufacturing cells do not require a DNC computer if only the CNC memory capacity is adequate to introduce the machining programs of all workpieces to be machined during the unmanned continuous operation. It's also necessary to ensure chips removal during this time. The structures of a manufacturing cell may be based on various machining centers.

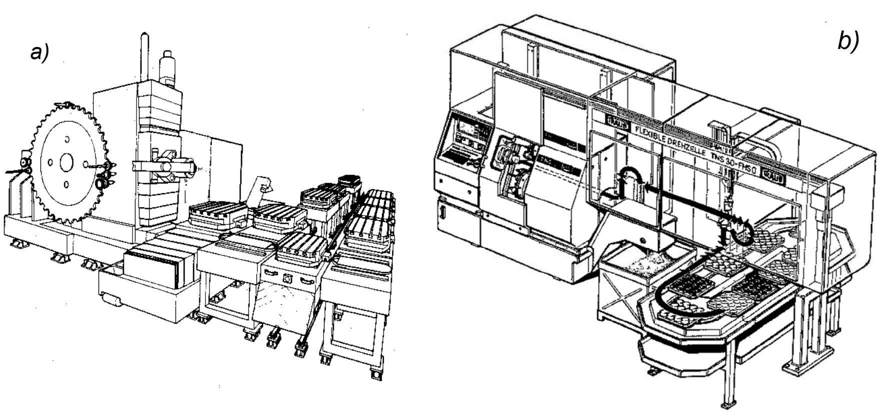



Fig. 3.4. Flexible manufacturing cells: *a)* milling, *b*) turning

The *flexible manufacturing island* – FMI (Fig. 3.5) in comparison to the machining centre and manufacturing cell is a system consisting of many machine tools and other manufacturing equipment, which from design point of view forms separated part of production department.

A flexible manufacturing island enables to carry out all necessary machining operations. The workpieces of certain limited spectrum create principally a group of technological similar parts. In FMI there are included besides NC machine tools (and other equipment) also conventional machine tools manually operated, particularly to make seldom carried out operations which are not worth of automation.

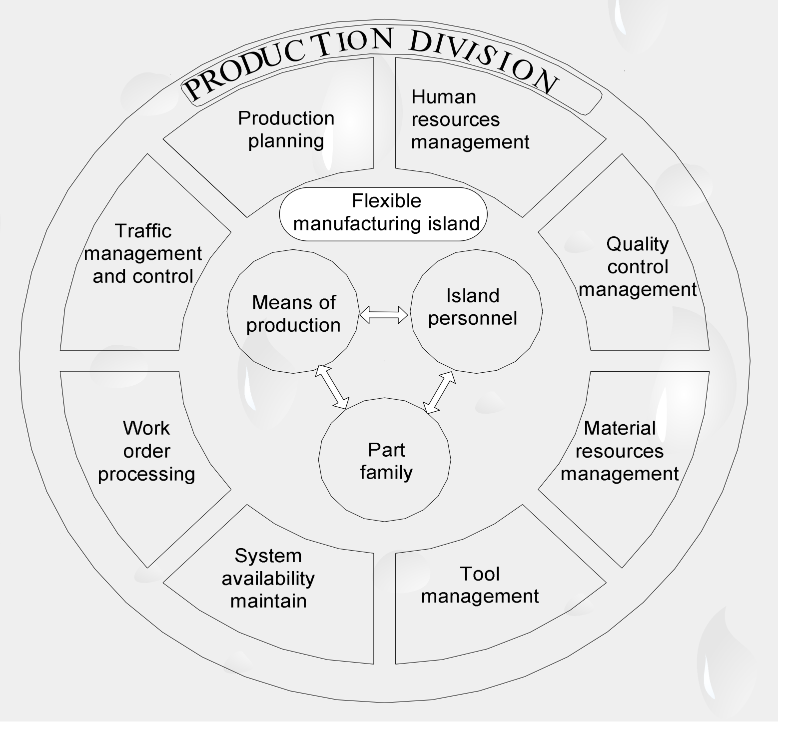



Fig. 3.5. Organization of Flexible Manufacturing Island

A team of appropriately trained personnel operates FMI, whereas this does not mean a rigid division of work-range between particular workers. As a rule, every worker should be able to solve each problem pertaining to island's operation. It is one of conditions of its flexibility. It is reached by decreasing the overall costs, shortening the time to make decisions, possibility to give-up of detained planning to realize duties of production order. Often the weakness of FMI is that the machine tools included in the island are not fully utilized.

The concept of flexible manufacturing with the highest grade of automation is the *Flexible Manufacturing System* - FMS (Fig. 3.6). It consists of a group (5-10) of highly automated machine tools which – working independently of themselves - realize in due measure, complete machining operations of the same, or similar parts. The machine tools are connected each other with a transport system, and the whole system is controlled usually by a host computer.

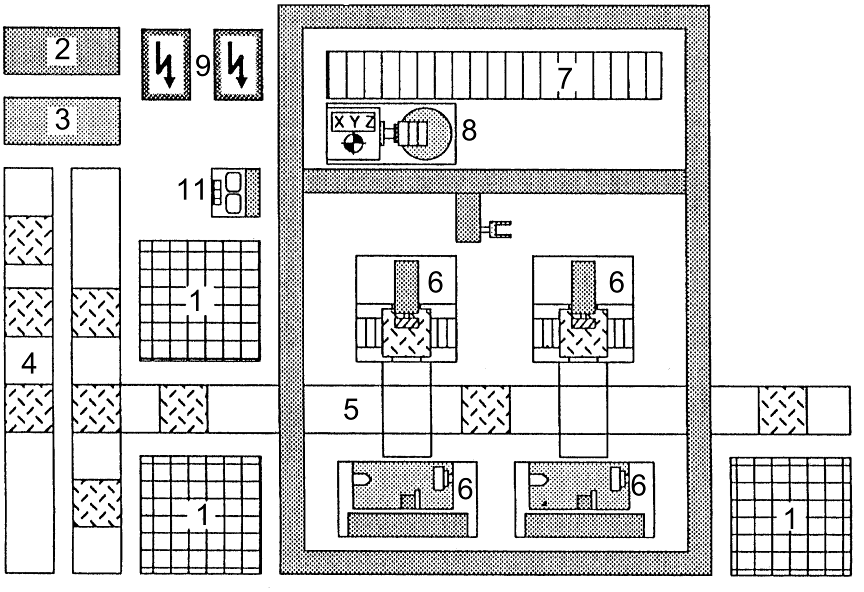



Fig. 3.6. The main units of a flexible manufacturing system: 1 – part store, 2 – fixture store, 3 – fixture/pallet assembly building station, 4 – queue area, 5 – pallet moving system, 6 – machine tool, 7 – cutting tool store, 8 – tool preset gauge, 9 – control system, 10 – cutting tool moving system, 11 – supervising station

It enables the following:

- Fully automated manufacturing,
- Making various machining operations of workpieces belonging to a part family,
- Machining the workpieces of variable batches volumes,
- Avoiding breaks in production caused by operators interference.

To use fully these possibilities, there is a need of a developed system of supervision and diagnostics. In FMS, we can employ with a different arrangement of machine tools and other manufacturing equipment. Depending on various transport means and the concept to solve transport ways, there are four basic structures of system (Fig. 3.7)

a) In-line structure
b) Closed-loop structure
c) Open-field structure
d) Ladder-type structure

a) <u>In-line structure</u> (Fig. 3.7.a) is most often applied by larry car transport. The machine tools and other equipment are placed on both sides of transport line. Advantage of the system is a compact structure (well-utilized work space) and ease to expand (through extension of transport line). Its disadvantage is a not easy access to machine tools by servicing and maintenance works and in case of removing the results of failure in system functioning.

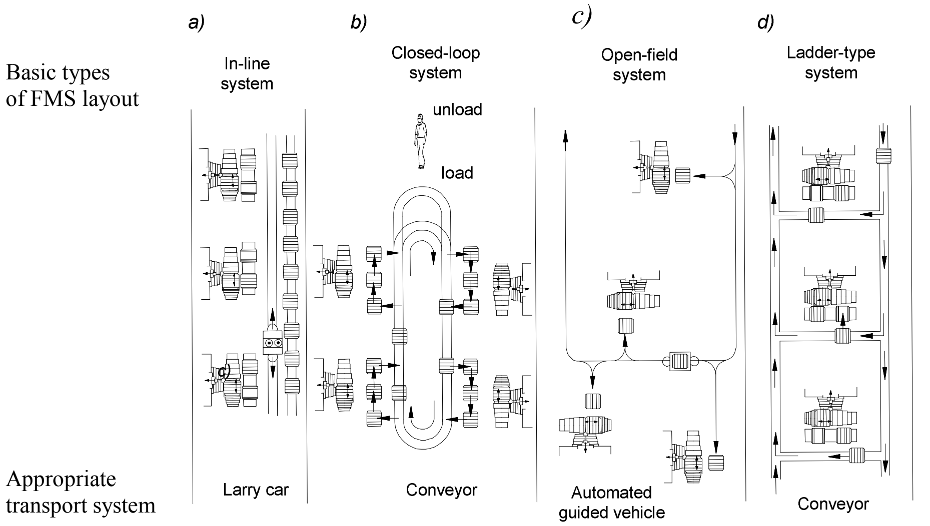



Fig. 3.7. Basic FMS layout types

b) <u>Closed loop structure</u> (Fig. 3.7.b) here the transport path is in the form of closed oval, round or rectangle circuit of conveyor system. The workstations are located outside of this circuit. Pallets remain in continuous circulation until the end of machining. Thereafter, they usually leave circulation through the washing stand and return to beyond the unloading stand. Advantages and disadvantages are similar to those of linear structure.

c) Open-field system (Fig. 3.7.c) in which the manufacturing equipment is freely spaced on a given surface according to conditions of technology, or system requirements.

   The transport system, connecting particular workstations is realized by:

   - Automated Guided Vehicles (AGV), most often wire-guided, or
   - Gantry robots, in case of small numbers of machines and little surface being under operation.

   Advantages: free access to particular stations and good possibility to expansion.

   Disadvantages: large surface occupied and long transport ways.

d) Ladder-type structure (Fig. 3.7.d) - its specific feature is, that pallets run on conveyor round all the machine tools waiting on buffer sections until appropriate machine tool will be free. In transport systems are used most often gravity roll conveyors with a double belt (Bosch). After machining, the pallet with work-piece is delivered onto conveyor and returns to behind unloading station. The great disadvantage of this structure is that each machine tool is surrounded by transport system and the access to it is very difficult. Due to this fact, this structure is not recommended.

*Flexible production line* – FPL (Fig. 3.8) - is distinguished from conventional lines first of all by the use of NC machine tools and other equipment like robots and manipulators. Machine tools are situated one by one along the transport path. The parts follow then from one stand to another in beforehand ordered sequence and are machined according to the following various machining program. Flexibility of line, results from the ease of resetting the tools to machine various product batches, and the easiness of programming the machining procedure and of possibility to expand the line and retain the existing machine tools and the ways of material flow. By changing the structural system of FPL, one can increase in certain limited range its flexibility. The line with compensation stores (fig. 3.8.c) gives namely the possibility to part loading and unloading without the necessity to pass through the all stations. The flexibility of line can be also increased using transport system, which allows omitting certain stations, or passing without making machining operations.

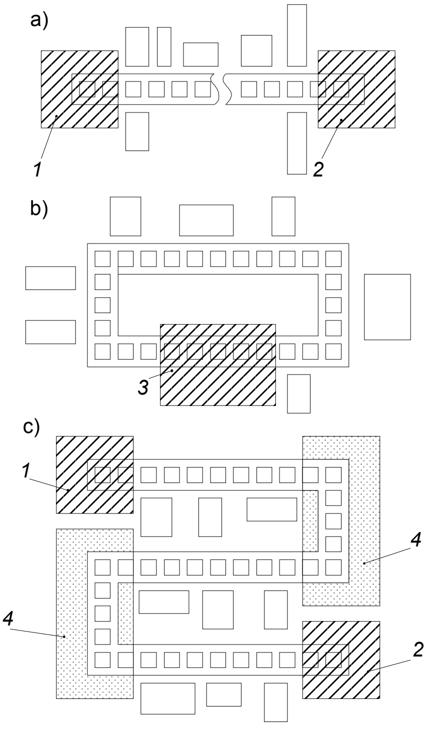



Fig. 3.8. Flexible production lines structures:
a) single row line, b) closed loop line,
c) line with compensation store
1 – loading, 2 – unloading, 3 – central load/unload station, 4 – compensation store with possibility of part loading/unloading

It should be also emphasized, that the conventional machine lines and special machine tools present usually markedly greater effectiveness than flexible systems.

In case of differentiation of machined workpieces and short series, they do not however form rational alternative for those systems.

The concepts of flexible manufacturing automation discussed herein are placed in area of the so-called "completely processing". Under this notion, there is a possibly complete machining of a workpiece in one fixing, thanks to far-going integration of various processes of machining, and of methods of manufacturing by one machine tool, fixture or manufacturing system. The tendency to complete machining is associated with the aim to increase the effectiveness of manufacturing, ensuring simultaneously a high accuracy of machining and then the quality of manufactured products.

# 4. FUNCTIONAL STRUCTURE OF FLEXIBLE MANUFACTURING SYSTEM

Considering the functioning of any technical device, or attempting to design such one, it must be first clearly defined the aim to which it must be used, and as defines J. Dietrich [8] its basic "right to exist”. To it namely, will be subordinated the functional structure and consequently, the project of the whole system. The main goal of a Flexible Manufacturing System can be formulated as follow:

*Economically effective part processing by wide part variety, randomly schedule and variable batch size.*

To achieve this goal, in general case of a complex system, the following should be ensured:

- Sufficient inventory of parts and tools,
- Automated part moving,
- Automated tool movement to and from the processing stations with transfer of tooling data,
- Remote distribution to machine control units and actuating of NC programs,
- Automated chip disposal,
- Automated cleaning of parts, fixtures and pallets on machine tool or in wash-station,
- Automated workpiece inspection on machine tool or inspection station (coordinate measuring machine),
- If necessary, a main computer and/or DNC system,
- In accordance with needs, central monitoring and diagnostic system

The realization of these requirements is made through fulfilling of determined functions. All functions, which are, or may be realized in a flexible manufacturing system, can be grouped in three main functional subsystems (Fig. 4.1), closely connected each other and with surroundings.

The flexible manufacturing systems are now present most often in the area of machining. In such a case, the technical system consists of the main following subsystems: machining system, tool management system, part management system, and supporting systems: energy management system, auxiliary materials management system and chip disposal system (Fig. 4.2).

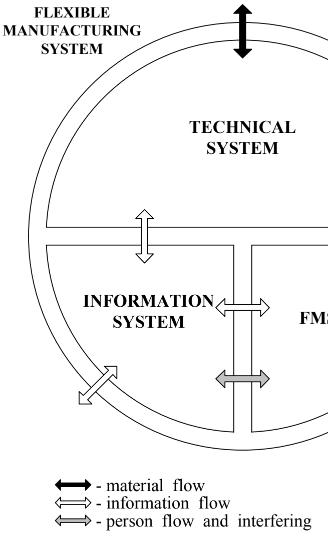



Fig. 4.1. The main functional subsystems of a flexible manufacturing system

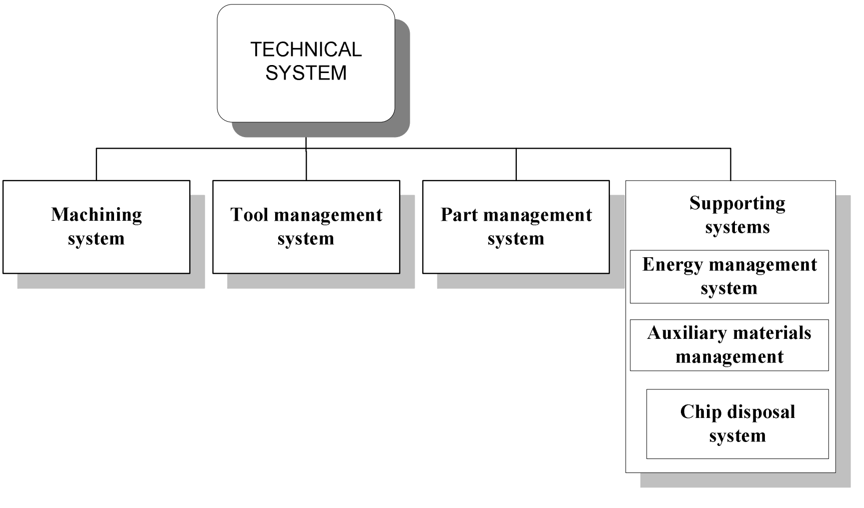



Fig. 4.2. Subsystems in FMS technical system

The *information subsystem* realizes functions (Fig. 4.3) necessary to control and supervision of processes running in FMS. There can be distinguished from it two main subsystems*: data distribution and collection* and *short-term planning and control of manufacturing process.*

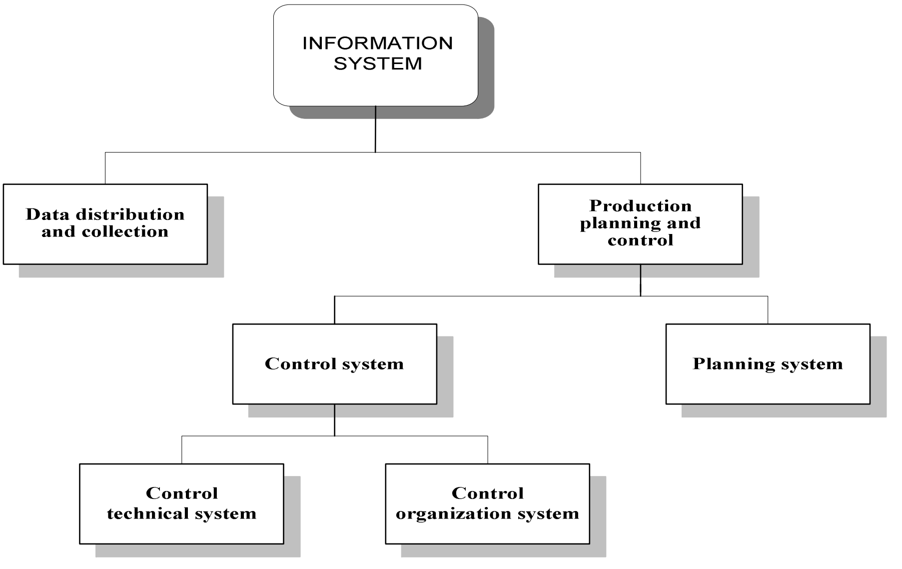



Fig. 4.3. Components of information system

The *data distribution and collection* subsystem ensures:

- Storage and retrieval of all data connected with part machining planning and control in flexible system. Therefore, watched must be the condition of each part being machined in a given moment in the system. The matter is, to manage the technological process (together with demand for tools for particular machining operations and suitable NC programs), and to watch the machining course.
- Management of tool matrices and tool cycle time expectancy.
- Collecting data stored at the machine control unit to maintain a historical maintenance and cumulative run time log.

The short-term *planning and control* subsystem includes managerial and execution functions necessary to ensure coordinated course of part processing, handling and moving in FMS.

*Planning system* includes, with regard to the actual condition of FMS, tasks connected with loading of the technical system with realization of work-orders released by the system manager. It defines an individual work order to the FMS and describes its station processing sequence.

In the *control* system there may be distinguish two subsystems: the technical and the organizational subsystems. The first one ensures:

- Sending the part programs
- Control of part and tool flow (e. g. watching the positions of AGV's with the aim to avoid collision).
- Synchronization of machine tools and transport control, as well as,
- Control of particular machine tools.

The role of *organizational* subsystem is on the other hand short-term planning (machine tools operation, using transport means, changing the dispositions in case of failure in working of the system), and run time log. As far as in the conventional manufacturing, the last problem is very often omitted, but in flexible manufacturing systems, its realization is considered as a necessary condition of its operation.

*FMS staff* subsystem covers the personnel directly engaged in operation of FMS. In many cases in planning of the flexible manufacturing systems, this problem is not separated and discussed and there may exist such impression that FMS can be operated fully unmanned. This is however possible only during limited period of time (unmanned shift). The work-task of *FMS staff* sub-system covers: preparing of parts and tools (building of pallet and fixture assemblies, loading of parts on pallets, building up and tear down of tool assemblies, tool preset, tool delivery, tool allocation, supervision of manufacturing process, maintaining of all facilities, and also in many cases (computer aided) control. It happens namely, that the interference of a man in the process running is necessary. And so, e. g. a decision about which part should be as the next transported to definite machine tool and then machined, is often left to a person supervising the operation of the whole system. There is a tendency to minimize the division of work-task among the personnel of the FMS staff. It increases markedly its flexibility, but requires appropriate training of workers so, that they would be able to perform various operations. This aspect has a particular meaning in non-automated flexible manufacturing islands.

To decrease the investment risk, one should assume that the planned flexible manufacturing system should have a modular structure. It means, that it can originate gradually by adding consecutive modules and in similar way; it can be expanded in case of need.

The most important components of the system are:

- Manufacturing installations according to the requirements of FMS; provided with standard part and tool interfaces,

- Feeding system for machined parts; equipped with means of part transportation, handling and storage,
- Feeding system of machine tools being in the system, with tools, together with necessary means of transport thereof, handling and storage,
- Control and supervision system

Modules included in these systems may be used to create FMS, accommodated in the best way to individual needs of the user. It allows reducing the necessary outlays connected with implementation of the system, and decreasing the investment risk. The development tendency is the standardization of interfaces and modules so, as to have the possibility to assemble a system out of modules produced by various manufacturers.

# 5. MACHINING SYSTEM

From the point of view of the right for existence of manufacturing systems being considered, the subsystem of giving the shape and property of machined parts is the most important. In this system is namely realized the basic transformation i.e. the change of material on the entry into finished part on the end.

Between the basic manufacturing methods, such as casting, plastic working and the machining, the requirements of flexible automation fulfill in the best ways the last one. The first realization of flexible manufacturing systems covered exclusively the machining process. Later, there were included the grinding machines, and at present, to the flexible automation of manufacturing, there are being included machines for electrical discharge machining (EDM) and for plastic forming.

The main goal of machining subsystem is:

*To give the workpiece suitable properties define in design documentation, i.e. first of all, the required shape, dimensions, and surface quality"*

In order to achieve the above goal, there must be realized several functions which may be shown in three areas:

- Shape creating process,
- Cutting process,
- Auxiliary functions.

The functional area of the shape creating process covers the realization of all relative motions of the workpiece and tool necessary to give the workpiece assumed shapes and dimensions.

In the area of the cutting process, there are functions, which are bound with the physical process of removing of allowance from the workpiece and to give the assumed properties to the surface of the processed part. To this range there have been included also such functions as chips removal, deburring and washing as well as inspection measurements.

The unmanned operation of machining and grinding is connected with the necessity of automation of necessary auxiliary functions, such as application of cutting fluids and chips removal. In automated manufacturing systems, these functions are integrated in centralized structures operating in all workstations.

## 5.1. PART SHAPE CREATING SUBSYSTEM

The aim of this system is:

*Creating of the part shape trough realization of relative movements of the workpiece and cutting tool in accordance with records of the design and technological documentation.*

Each of the forming movements is oriented in the space through giving the direction (in case of linear motions), or the axis of revolution (in case of rotary motions). Units, which realize the movement, are generally named "*NC axes"*.

A NC axis consists of:

- Controllable drive,
- Measurement system, and mostly, at least one
- Feedback loop.

The block diagram of machine tool cross-table NC axes is shown on Fig. 5.1.

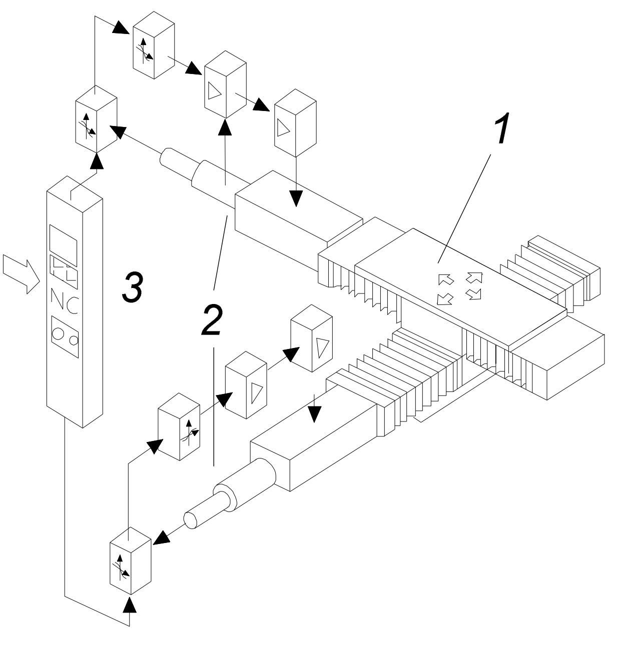



Fig. 5.1. NC axes of a cross-table: *1* – cross-table, *2* – NC axes, *3* – machine tool control unit

The functional structure of a NC axis is shown on Fig. 5.2.

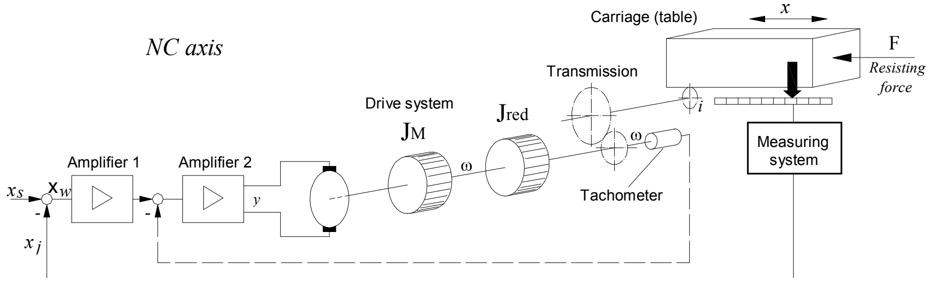



Fig. 5.2. Structure of a NC axis: $\mathbf{J}_M$ - motor moment of inertia, **J**red - reduced transmission moment of inertia

In the NC axes there may be realized both the linear and the rotary motions.

On the Fig. 5.3 is shown the diagram NC axes of a machining centre, on the Fig. 5.4.a of a lathe and on the Fig. 5.4.b, of a turret lathe.

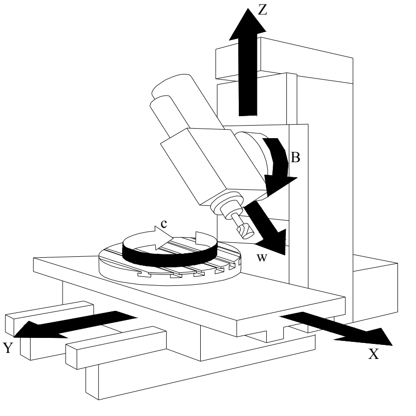



Fig. 5.3. A vertical machining center with NC axes: four linear and two rotational

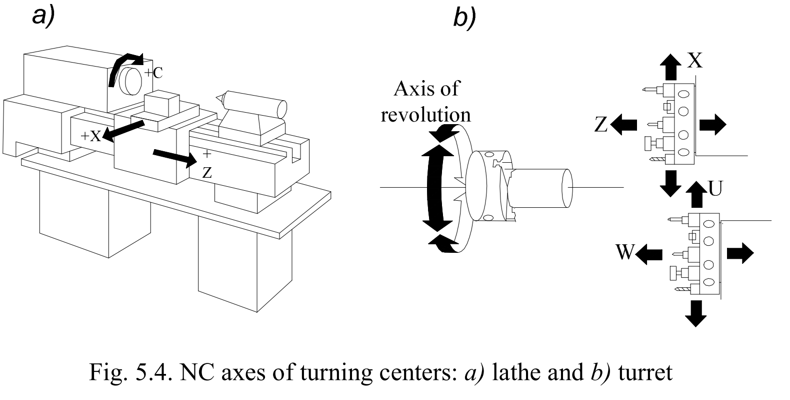



Fig. 5.4. NC axes of turning centers: *a)* lathe and *b)* turret

In case of lathes shown on Fig. 5.4, one of the NC axes is the axis of spindle rotation (*c* axis). The spindle, besides of fulfilling the basic matter, that is a unit performing the main working motion, has the possibility of precise angle positioning and rotary feed. This possibility may be obtained thanks to independent drive of this axis with backlash-free worm gear transmission. Since the spindle is provided with NC axis, it enables to perform, by the lathe, to make on the workpiece, without changing its fixing positions some milling operation and to drill holes in planes rectangular to the spindle rotation axis. The spindles of lathe centers are usually provided with NC axis.

The basic components of flexible manufacturing systems are the machining centers. They have been developed at the beginning of 1960s and were designed mainly to perform the milling and drilling operations. Actually, the processing possibilities of the centers practically cover all machining operations. The classification of machining centers is shown on the Fig. 5.5.

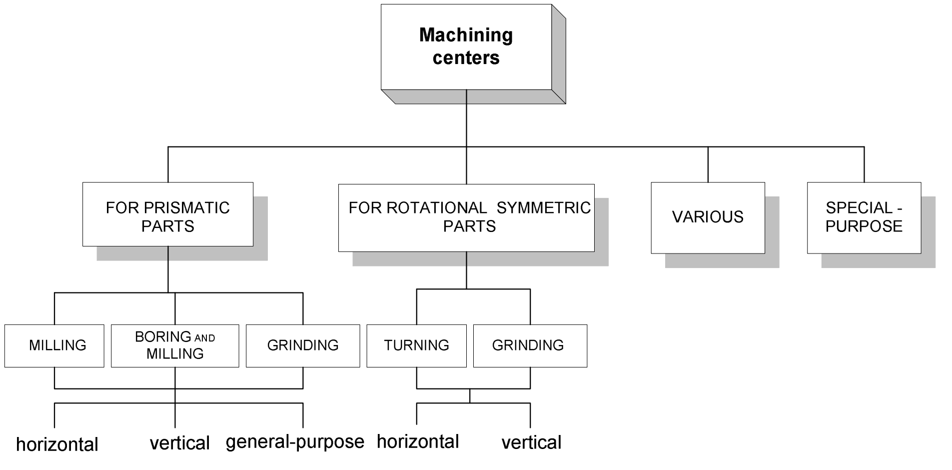



Fig. 5.5. Classification of machining centers acc. to L.T.Wrotny [129]

In numbers, in the best way are represented the centers to machine plate and boxy type parts, especially the earliest created milling centers, the milling-boring and boring-milling centers. Usually, they are provided with at least four NC axes and enable to make also drilling operations (drilling, threading, reaming). These centers are classified as either vertical or horizontal and as universal ones with angle head, which can be turned by any angle. An example of basic module of machining center is shown on Fig. 5.6.

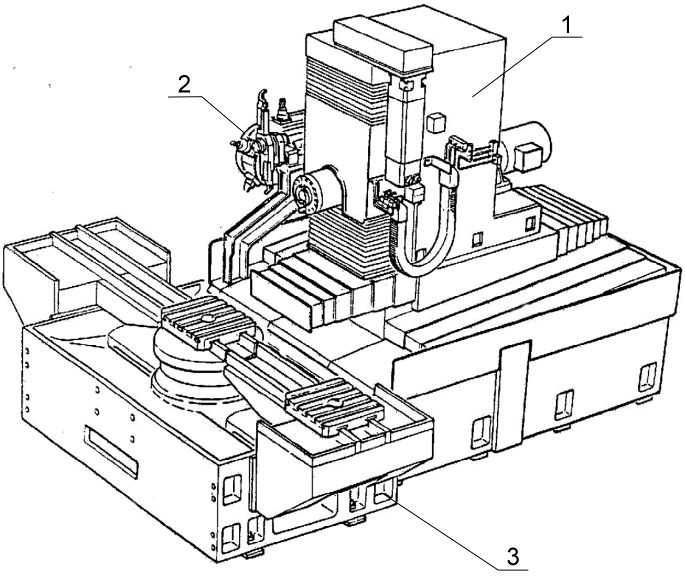



Fig. 5.6. Basic module of horizontal machining center used in flexible manufacturing systems:
1 – machine tool, 2 – tool magazine, 3 – pallet changer

Design structures of centers are characterized by:

- High rigidity of spindle system,
- High bed rigidity,
- Thermo symmetric frame structure,
- Spindle structure enabling repeatable conditions of tool fixing,
- Good flow of chips and cutting fluids,
- Enclosed workspace.

Following the machining centers, the turning centers appeared (considerably late, because of the 1980s), and then, the grinding centers for gears machining and others. In the group “various”, in the Fig. 5.5, are such center as: cutting off centers, electro discharge machining centers, or laser centers. Under the term, “special” there can be included centers of explicitly narrowly directed production destination. Besides, of machining centers, there are used in FMS drilling machines with multiple-spindle heads. In case of repetitive hole patterns it results in shortening the machining time and make less loaded, usually more expensive machine tools.

To ensure economic effectiveness of FMS from the system equipment, and first from machine tools, it is required high availability level. This will be achieved trough:

- High machine tool reliability,
- Functional reliability of control,
- Short repair times.

The most important feature of a machining center is a fully automatic operation in the process of machining, without operator's interference. Operator of a machine tool usually makes the following: fixing and releasing of the workpiece, inspection of machine tool operation and condition of tools, inspection of the machined part. To ensure the possibility of unmanned operation, all these functions must be also automated. Due to, first of all, shortening the time of realization, as well as due to economized place and reliability of operation, it is to great advantage that the structure realizing these functions (and also other ones), would be structurally related to the machine tools. In this way, the centers have been developed into "flexible manufacturing cells". These additional installations, which automatize the operation of machine tool, are present in its workpiece system, tooling preset and monitoring, machining liquids and chips removal.

The machine tools used in FMS are usually marked with a great efficiency. This cause that the volume of chips produced in unmanned operation is substantial and the use of cutting fluids is also great. The problem of chips disposal is solved usually as a whole for the system, whereas the machine tool must be provided with installation to remove the chips to a central conveyor.

A great amount of cutting fluids is partly used also to wash after machining the workpiece, the fixture, and pallet directly on the machine tool. Therefore, there exists the necessity to use screens protecting the surroundings of splashed coolant. Such screens reduce also considerably the noise emission resulting from the machining process and the machine tool operation.

## 5.2. METHODS AND EQUIPMENT FOR DEBURRING AND SURFACE FINISHING

Deburring is a particular machining operation. It relies on removal of burrs, which usually remain on edges of machined parts, on casting parting plane, or on edges of sheet metal after shearing or cutting.

Need for part deburring results from many reasons:

1. Burr may cause product malfunction in use and increase the wear of interacted parts,

2. Burrs, particularly on hole edges, may disturb or make impossible automatic assembly,
3. Burr sharp edges may cause injuries by assembly or use of product.
4. Burrs worsen the product appearance.

In conventional manufacturing, burrs removal was usually, besides of particular cases, a secondary question. This problem became significant in automated manufacturing. As a result, is the arising, in the last years, of international range organization, which elaborate standards containing, among other things, definitions of technical notions, pertaining to burrs and specification of burr types [28].

Burrs in machined workpieces are real productivity killers. Not only they require additional finishing operations (deburring), and complicate assembly, but also these operations can damage the part. Handling parts with burrs is a challenge for workers. Ideally, we would like to avoid or at least minimize burrs by careful choice of tools, machining parameters and tool path of work material and part design. In fact, most burrs can be prevented, or minimized with process control. Recently, more research and interest has been focused on problems associated with burrs originated from machining. The focus has traditionally been directed on deburring process, but understanding the burr formation process is critical to burr prevention. However the level of scientific knowledge on this problem is just developing. It is vital to be able to associate details of the part performance and functionality with requirements for edge condition. Standards and specifications are only now being developed for this problem.

To effectively address to burr prevention, the entire "process chain" from design to manufacturing must be considered (Fig. 5.7 according to [9]).

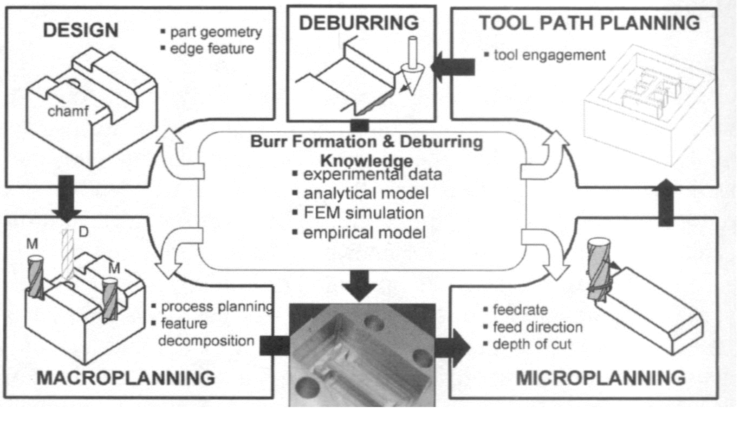



Fig. 5.7. Components of a comprehensive approach to burr prevention and minimization.

Minimizing or preventing the burr formation requires that all stages of manufacturing, from the design of the component, through the planning and production would be integrated so, that the potential part features and material constrains, tooling and process sequences and process variables from the point of view of creation of burrs on the workpiece would be considered.

In situation where burrs cannot definitely be eliminated in the process of machining, they must be removed in a separate operation. First, there should be selected appropriate methods of removal, what will often be associated with the necessity to use special machines and equipment. The economic effectiveness of defined deburring methods depends on the following factors: required accuracy of this operation, number of machined workpieces, time of duration of burrs removal of one part, workshop area necessary to arrange a workstation on which the operation will be realized, and on safety rules and environment protection.

During the last 30-35 years, many such methods and associated equipment appeared including NC machine tools. The most often used can be divided into five groups, which enclose 1. Mechanical, 2. Thermal energy, 3. Electrochemical, 4. Vibratory, 5. Jet method.

### 5.2.1. MECHANICAL METHODS

The possibility of using appropriate kind of mechanical treatment depends on material and geometry of machined workpiece as well as on quantity and type of burrs. There are applied the following methods: machining, grinding, loose abrasive treatment, and using of the wire brush.

The use of loose abrasives belongs to intensively developed and finding still widening industrial application in mechanically removal of burrs. The feature of these methods is integration in one operation the finishing treatment of workpiece surface and burrs removal on its edges. American firm "Extrude Hone" which offers also a range of equipment for deburring has elaborated several methods belonging to this group. Between the methods using loose abrasive, belong the following:

- Abrasive Flow Machining (AFM) – consists on pressing through the holes and channels of subject (or around it) a viscous-elastic abrasive polymer,
- Orbital Polishing (OP) – in which the same abrasive material is used,
- Ultrasonic Polishing (UP)

The abrasive material used in AFM and OP methods is a plastic polymer, of special rheologic properties, containing the abrasive material. The firm "Extrude Hone" offers a range of these type polymeric materials of various abrasive properties enabling to gain various treatment effects, from smoothing, to aggressive removing of material allowance. The used pressure of forcing through is in the range of $7 \cdot 10^5$ Pa to $200 \cdot 10^5$ Pa depending on quantity of necessary displacement of pistons and the number of forcing through cycles.

The abrasive flow machining can be easily automated. The firm "Extrude Hone" delivers complete stations containing also equipment for cleaning and washing including the station-operating robot.

## 5.2.2. THERMAL ENERGY METHODS

Thermal energy deburring uses intense heat to deburr and/or deflash parts. Parts to be processed are sealed in a chamber that is pressurized with a mixture of combustible gas and oxygen that completely envelopes the parts and surrounds burrs and flash, regardless of external, internal, or blind hole location (Fig. 5.8).

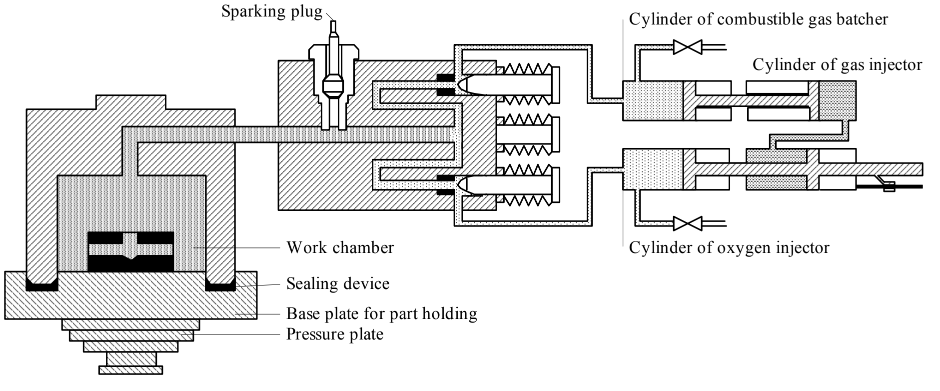



Fig. 5.8. Functioning principle of thermal energy deburring

This gaseous mixture is then ignited by a spark plug, which creates an instant burst of intense heat (temperature from 2500 to 3500 °C), and burrs and flash, because of their high ratio of surface to area mass, burst into flame. Burrs and flash are instantly oxidized and converted to powder in a total floor cycle time approximately 25 to 30 seconds. Part can then be cleaned with solvent.

Thermal energy is a unique and consistent deburring process because it removes undesirable material from all surfaces, even inaccessible internal recesses and intersecting holes. It is effective on a wide range of dissimilar parts of both ferrous and nonferrous material.

### 5.2.3. ELECTROCHEMICAL METHODS

The „electrochemical" method of burrs removal consists on anodic digestion of material. Electrochemical deburring machines can deburr and contour parts through an electrochemical reaction that dissolves metal from a workpiece into an electrolyte solution. Direct current is passed through the electrolyte solution between the electrode tool (the shape of the cavity desired), which has a negative charge, and the workpiece, which has a positive charge. Chemical reaction caused by the direct current in the electrolyte dissolves the metal from the workpiece. Although electrochemical deburring is a slow process, it has several advantages. The tool (electrode) never touches the part, so no tool wear occurs. No heat is created during the process; therefore, thermal or mechanical stress cannot distort the part. And electrochemical deburring is applicable across a wide range of material types and hardness variations. One should however take into consideration, that the wasted liquids strongly load the environment and require neutralization, thus increasing the cost of operation.

### 5.2.4. VIBRATORY METHODS

In the last period of time, still the widespread use finds the "vibratory" method of deburring. Vibratory deburring machines are designed for relatively small rotational or prismatic workpieces. Parts systematically enter a large bowl container filled with ceramic pebbles commonly referred to as media. The size of the ceramic media can vary depending on the type, size, and material of the parts to be deburred. As parts enter the bowl, sometimes via a conveyor, the rapid vibratory back and forth, motion agitates the parts in the ceramic media, removing burrs, descaling, and gently polishing the parts. Eccentric weights are mounted on each end of the container support shaft to vibrate the bowl in a controlled but adjustable manner. As media can also used pieces of plastics, hard wood and crushed corncobs. The duration of treatment is 5 to 25 minutes. The effectiveness of this process may be increased by the use of water bath with the addition of synthetic washing means, detergents and corrosion inhibitors. An additional effect is obtained in this way in the form of clean workpiece and abrasive elements and through rinsing from the system the treatment remainders. Duration of the process may by shortened even by 80 to 90%, decreasing also in the same grade the use of abrasive elements, using addition of chemically active means.

### 5.2.5. JET METHODS

The beginning of jet treatment of surfaces is recognized in patent of B. C. Tilgman (1870 year), whereas the development of industrial application is dated on 1930s. Its substance consists in giving a great acceleration for a medium, which is in the form of liquid or crushed solids, and directing it on the treated workpiece's surface. The effects of action of medium stream depend first on material used and on energy concentration grade. There are now many known and used methods included in this group of various applications, also for burrs removal. In particular there are now being developed, burrs removing with a stream of "high pressure liquids", although in certain cases there are also used the stream-abrasive methods.

Besides of methods, which can may be included to the described five groups, there are known also another methods, rarely used, or being in experimental phase.

### 5.2.6. PRINCIPLES OF DEBURRING METHOD SELECTION - COSTS OF DEBURRING

The selection of most suitable, in a given case, method of burrs removal depends on a range of factors such as material of machined parts, part dimensions, position of edges being treated (external, hidden), geometrically defined edge (in case of castings, there is a great diversification in particular pieces) geometric form of burr (its length and cross-section), allowed actions on the part's surface, operations made before and after burrs removal, possibility to change the sequence of operation due to removal of burrs; and also on the answer such questions as:

- Can the thermal and/or mechanical stress influence the part?
- Is the thermal treatment planned?
- Which range of burrs removal is necessary (if it will be sufficient to remove the protruding burrs, or it will be necessary also to break the edges)?

Taking in consideration both the mentioned factors, as well as the response on given questions, it allows to take optimal method of the process of burrs removal, having in view the cost of operation and its durability.

The costs associated with burrs removal are substantial. The typical costs as a percentage of manufacturing costs varies up to 30% for high precision components such as aircraft engines, etc. In automotive components, the total amount of deburring costs for a part of medium complexity is approximately 14% of manufacturing expenses. The actual investment in deburring systems increases with part complexity and precision (Fig. 5.9).

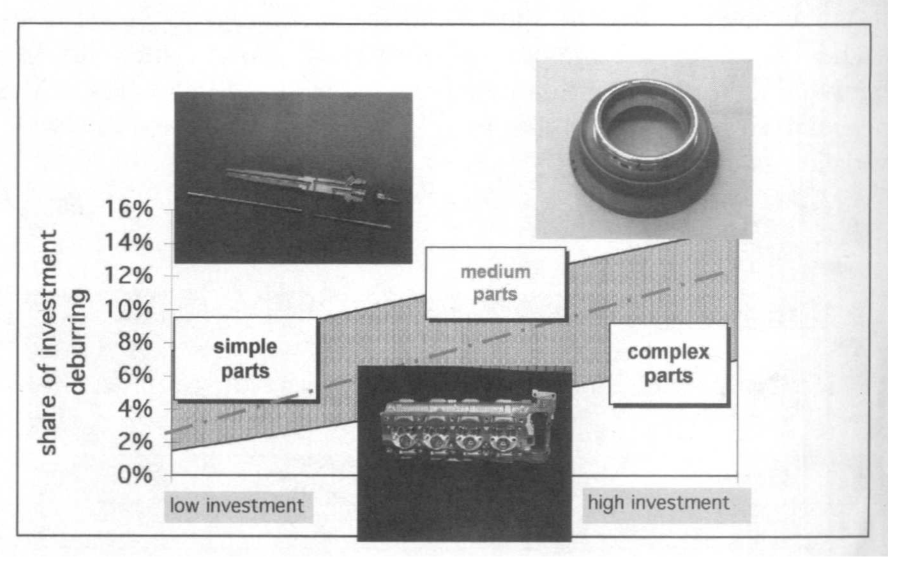



Fig. 5.9. Investment in deburring systems as a function of part complexity and total investment in manufacturing system [9]

## 5.3. REALIZATION OF AUXILIARY FUNCTIONS

The realization of machining process is associated with the use of coolant. By planning and implementation of automated manufacturing systems is then necessary to solve the problem of supply the machine tools with this cutting fluid.

Part processing in the area of machining requires steadily removal of chips and other waste materials from the workspace. It is also necessary to wash (often many times) the workpieces, tools, fixtures and pallets. The unmanned operation of manufacturing system is also impossible without automation the auxiliary functions. Structures, which realize these functions, create the infrastructure of flexible manufacturing system.

When planning the manufacturing system it is recommended to provide for a system of chip disposal and of supply the workstations with coolant, which in the best way can be placed under the floor [29]. It will be avoided in this way placing between the stations complex structures of pipelines and conveyors, making it difficult both the access to the stands, as well as the possibilities to change system layout.

COOLANT

The centralized feeding of manufacturing liquids and chips removal is also advantageous due to costs of these installations [2]. It makes easier to neutralize the used machining liquids, what is necessary due to requirements of environment protection. Between the constituents, besides of water (about 90%) and emulsifiable oil there are many constituents being greatly harmful for a man and natural environment. (Fig. 5.10) [27]

**COOLANTS**

| Nonemulsifiable technological oils | Coolants on the water basis |
|---|---|
| - mineral oils<br>- synthetic and vegetable esters<br>- polyglycols | - mineral oils<br>- synthetic and vegetable esters + water<br>- polyglycols |

\+

**Antiwear (AW) additions**

- reducing tool abrasive wear

| | |
|---|---|
| - phosphorus compounds<br>- sulfur compounds | -fatty acid esters<br>- polyglycols |

\+

**EP (extreme pressure) additions**

- improving coolant resistance against extreme pressure

| | |
|---|---|
| - polysulfide<br>-fatty acid esters | - phosphorus and sulfur compounds |

\+

**Corrosion inhibitors**

| | |
|---|---|
| - phosphorus compounds<br>- sulfur compounds | - fatty acid esters<br>- polyglycols |

\+

**Dodatki Antifoam and antifog additions**

| | |
|---|---|
| - hydrocarbon polymers | - silicones, polysiloxanes<br>- organic polymers |

\+

**Emulsifiers**

| | |
|---|---|
| - | - sulfonates<br>- fatty acid amids<br>- aliphatic alcohols |

\+

**Conservation additions (biocides)**

| | |
|---|---|
| - - | - formaldehyde (derivative) |

Fig. 5.10. Components of cutting fluids

In the manufacturing systems, where in circulation is above 50m$^3$ liquid, there is profitable to introduce central coolant recycling and recovery system because recovering and recycling used and contaminated coolant is generally more economical then disposal and replacement [48]. On the Fig. 5.11 there is shown a schematic diagram of such installation in automotive factory.

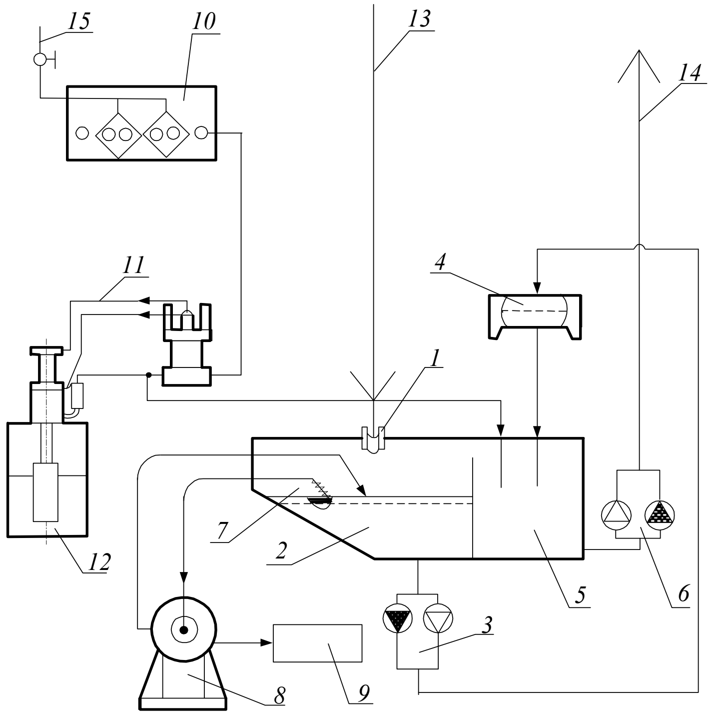



Fig. 5.11. Central coolant recovery installation: 1 – contaminated coolant sewer, 2 – central tank, 3 - pumps, 4 – coolant filter, 5 – clean coolant tank, 6 - pumps, 7 – pick-up flowing impurities, 8 – centrifugal separator, 9 – impurities to by burned, 10 – water softening, 11 – complementary additive feeder, 12 – additives container, 13 – installation of draining the used coolant from work stations, 14 – installation of feeding the processing stations with recovered coolant, 15 – water supply installation.

Thanks the recovery, the coolant may be used on the average for a period of 18 months (maximum even up to 3 years). After this period, it must be excluded from circulation and utilized. The recovery consists in its purification and addition the components in order to get constant chemical composition whereas utilization means removing the used liquid, which is not worthy to be utilized and not to pollute the environment. In the process of utilization, the coolant is cracked into components, which may be used for other purposes, or is burnt [27]. Without the recovery installation, coolant is purified only of floating impurities, must be exchanged once a month, or every two months. Taking in consideration the multiplied in this case, costs of neutralization and utilization of used liquid it must be stated, that such installation brings significant decrease of manufacturing costs.

The cutting fluids are an important component of manufacturing system. They fulfill in the manufacturing process a range of various purposes. They are shown, together with the effects of using the cutting fluid during the machining process, on Fig. 5.12.

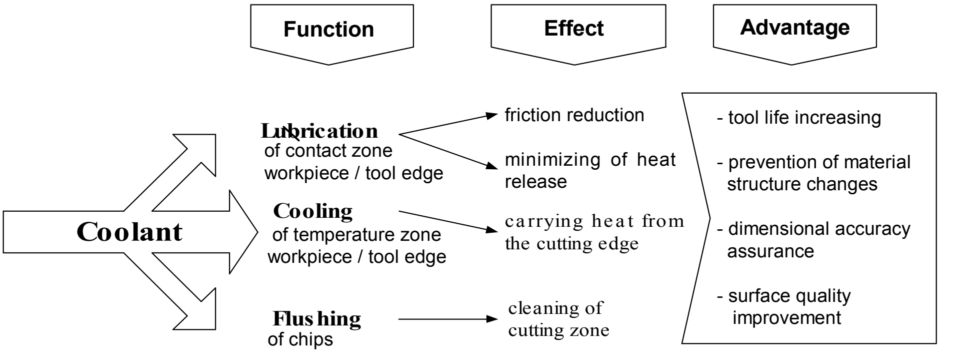



Figure 5.12. The role of coolant in machining

The economic significance of cutting fluids proved by the fact, that in the balance of production costs, the costs of using the coolant by part machining, includes also the outlays for neutralization after the use, reach to 20% of the costs of tools [56]. It is maintained since many years and shown the upward trend. It results not so much in increasing the use of these fluids, but tightening the regulations pertaining to the environment protection and what is also the necessity of neutralization and to use in them more expensive, but less harmful additives. It is also important to protect the atmosphere against the penetration of fogs and vapors. By intensive use of coolants, they are atomized by rotating parts (tools, or machined part), and also vaporize due to the action of high temperature in machining zone. To avoid the noxious influence of oil fogs in the environment, there are used air cleaners which it drawn-in from the workspace of machine tool (Fig. 5.13)

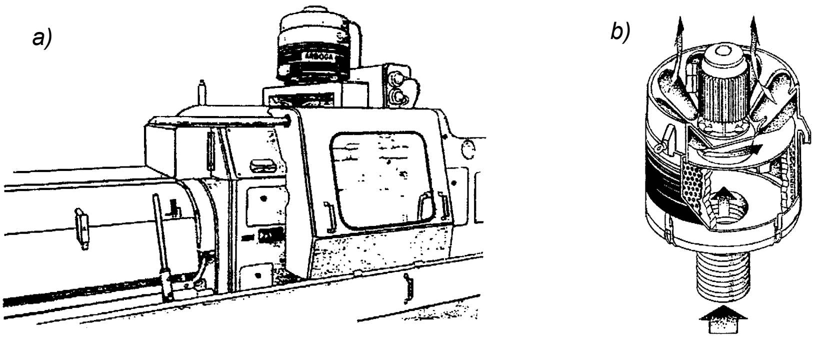



Fig. 5.13. Installation cleaning the air of oil fog from the working space:
a) installation placed on the machine, b) cleaning device (filter)

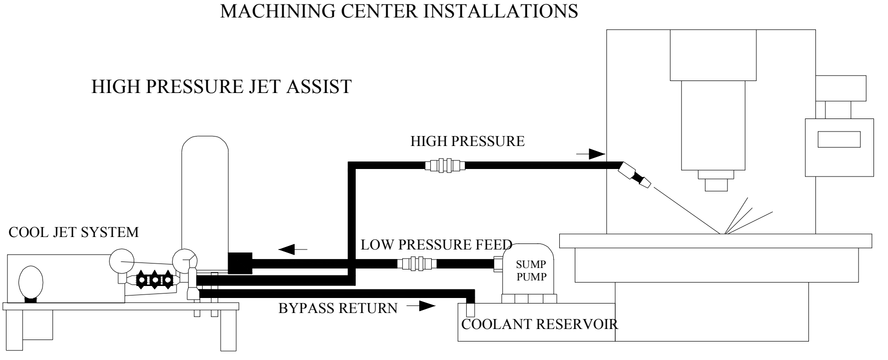
Whereas the abrasive machining is as a rule carried out with the use of coolants, then in the area of machining are intensively being developed methods, which allow to minimize, or eliminate them of use [21]. Dry machining means however to take in consideration such problems like tool life, and machining accuracy due to workpiece thermal deformation.

### 5.3.1. CLEANING SUBSYSTEM

Part must be cleaned between machining operations, or before they can ever attempt to be accurately inspected, stocked, or assembled. It is necessary also to wash the pallets, fixtures and tools. Often to cleaning are used the coolant, and hence, wash-station and the workstations may be supplied by the same system. In case when washing is associated with preparing of the part surface to make then operations such as coating or painting, other washing liquids are used. Generally, there are two types of the washing systems:

- Integrated with another manufacturing installations (machine tool or deburring station), and
- Separated wash-station.

Washing of parts on the machine requires delivering adequate volume and pressure of coolant for complete flushing of chips from the workpiece, fixture and pallet. On the Fig. 5.14 there is shown a schematic diagram of high-pressure installation of American firm “Cooljet Systems” (Berea, CA [2]).




Fig, 5.14. High-pressure washing installation

The coolant is delivered to the machining area under a pressure reaching 10 MPa. In order to ensure the effectiveness of influence of liquid stream, the nozzles can be numerically controlled, what enables their programming and automatic orientation to the workspace during the whole time of realization of the manufacturing process. So it is arranged in the systems "High Jet Center" of the firm Mitsui Seiki Inc." (Franklin Lakes, NJ).

In many manufacturing systems, using the coolant delivered to the workspace, part washing is carried out directly on machine tool after the end of machining (Fig. 5.15).

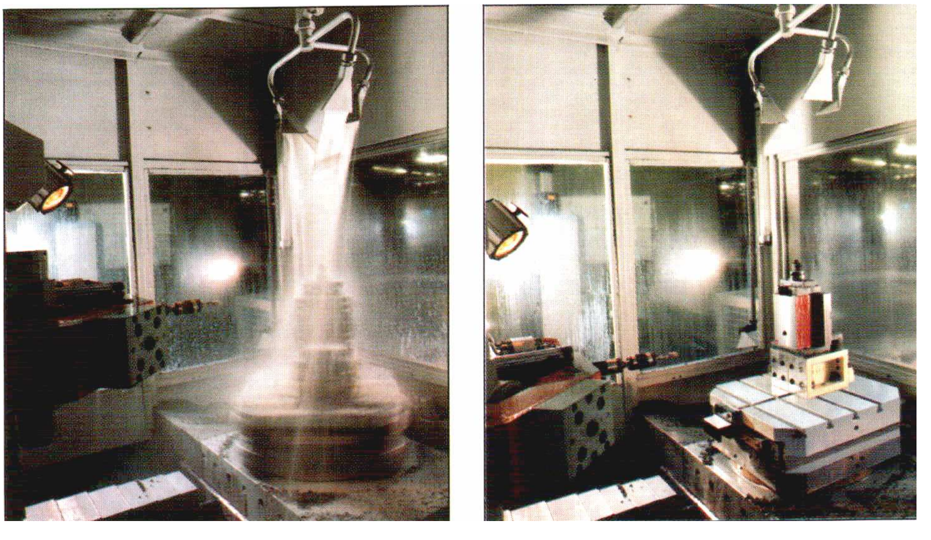


Fig. 5.15. Part washing in the working space of machining centers

The part is washed with coolant streams in workspace of a machine tool. This requires delivering the liquid with a system of nozzles and covering the working space. After washing part with the fixture and the pallet is blown with compressed air in order to remove the excessive liquids before changing the pallet. Using this way of washing is effective in case of parts where their machined surfaces have an easy access.

Another solution of part washing is the usage in flexible manufacturing system of wash-stations as separated workstations. Wash stations come in a variety of type, styles, and configurations, but are generally classified as either *batch* or *in-line conveyorized*. *Batch* washers are available to handle workpiece weighing thousands of kilograms and as large as a 2 meter cube. Batch wash stations are generally used in low- to mid-volume applications to provide a clean part for downstream inspections, assembly or further processing.

*In-line conveyorized washers* (Fig. 5.16) are used for high-volume production where rapid part throughput is a high requirement. With an in-line conveyorized washer, parts are loaded at one end of the system, cleaned as they pass trough the machine, and removed at the opposite end. Separate roller conveyors can be added at the load-unload sections for interfacing with a robot or pallet shuttle mechanism. Multiple stages can be added for rinsing, rust prevention, or part blow-dry.

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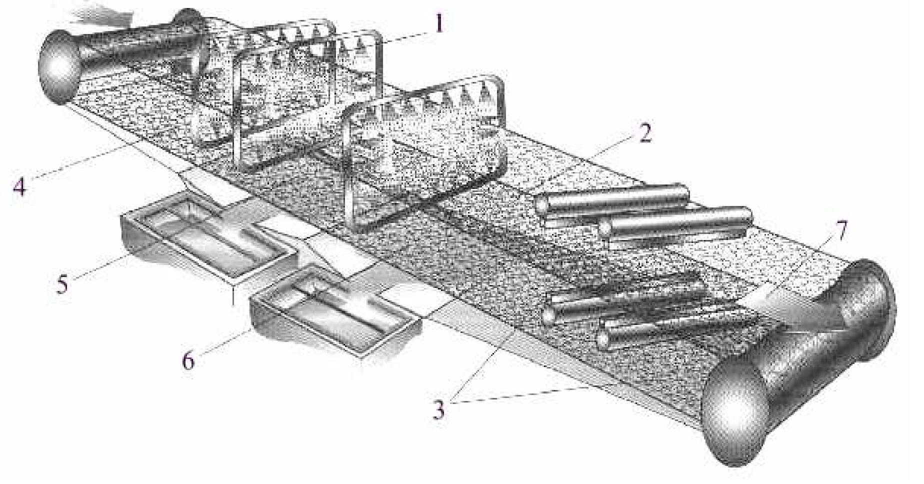


Fig. 5.16. Tunnel type modular conveyor washers: 1 – nozzles, 2 – steel net, 3 – nozzles of hot and cold air, 4 – conveyor tape of stainless steel, 5 – first section of washers, 6 – optional subsequent section, 7- optional heater of parts before leaving the washer.

Selection of either a batch or in-line conveyorized wash station is function of:

1. Workpiece type, size, weight, material, and configuration
2. Throughput rate required
3. Material to be removed (chips, cutting oil, tapping compound, und the like)
4. Succeeding operation type (inspection, stocking, assembly, or another machining operation)
5. Method of part loading, unloading, transport, and delivery.

As far as the washing media are concerned, the use of until now applied chemical media based on chloral-hydrocarbons, are recently changed by liquids based on water solutions of mild alkali washing media [41], what is associated with environment protection.

To part cleaning is also used a method of blowing with a stream of air (the blow-off method) [19]. Blow-off is one of the most important wash-station options. This reduces drying time of the washed workpiece by blowing off the excess coolant or wash solution, prevents spillover to other machines and other areas of the manufacturing system, and helps, keep the area clean and neat. Some machines use convector heated air blow-off generated by gas, steam, electricity in order to speed up the blow-off and part drying cycle and to remove moisture. An advantage of blow-off method is also low cost of installation.

Schematic diagram of a station for part cleaning by a stream of air is shown in Fig. 5.17.

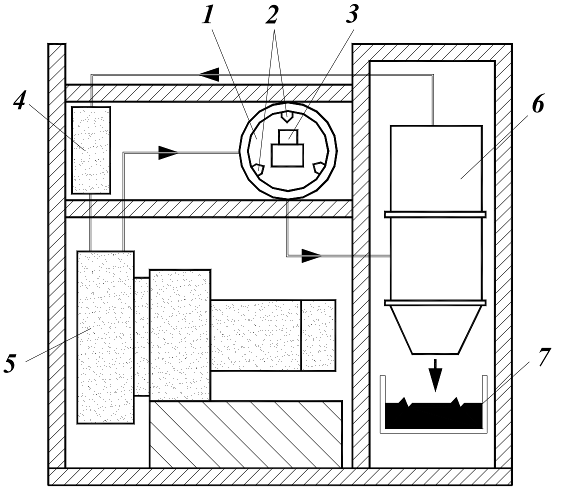


Fig. 5.17. Schematic diagram of air stream cleaning installation: 1- work chamber, 2 – nozzles, 3 – machined part, 4 – air cooler, – compressor, 6 – filter, 7 – oil

This method brings however also a range of limitations. First, it does not ensure exact part cleaning, from a remnant coolant. It suits then, first of all to interoperation cleaning, and also to preliminary cleaning before final, exact washing. This allows to markedly prolong the period of durability of the wash-station, and also to washing, with the aim to prepare the surfaces for further operations (coating). It may be used for parts of relatively simple shapes, having not hardly accessible spaces, and in case where there have been used technological liquids of low viscosity. Installations used for blowing the subjects with a stream of air can be easily integrated with manufacturing system.

### 5.3.2. CHIP DISPOSAL SUB-SYSTEM

A full automation of production cycle that is featured by flexible manufacturing system brings with itself also the necessity of automation the process of chips removal from the area of production [30]. To solve this problem, the following actions must take place:

1 – To ensure suitable form of chips which are easy to process (not continuous chip). This is obtained by the use, if possible, appropriate materials for the machined part, selection of suitable conditions of machining, the use of tools provided with chips breakers, or the use of special systems, which force controlled tool vibration in order to break up the chips. In case of necessity, there are applied systems monitoring the chip shape.

2 – Suitable design of machine tool framework ensuring free flow of chips, without being afraid, that they can stop and pile-up, creating the danger of interference of the working system,

3 – System of flushing the chips from the workspace,

4 – Chip transport system,

5 – System of chip preprocessing.

*Form of the chip*

In the machining, the form of a chip is resulting from the effects being presented in the area of contact of tool with the workpiece being machined and finds the reflection in the effects of machining and the course of the whole process. It decides about the ease of removing the chips behind the area of machining and the working space whereas in case of such processes as turning and drilling it decides about the amplitude of variable component of machining force.

Generally, there are recognized three basic shapes of chips:

- Discontinuous chips (splintering) formed by machining brittle materials; during formation thereof, there are present great variations of machining force what results negatively on the surface and are easy to convey behind the area of machining.

- Stepped chips (segment), are formed by machining hard materials with week thermal conductivity (such as e.g. high alloy steels, titan alloys); their formation is also associated with considerable changing if machining force. As a rule, they do not afford problems with removal beyond the machining area though they occupy greater volume of space than the discontinuous chips.

- Continuous chips are formed by machining materials of lower limit of plasticity (e.g. steel, bras, aluminum). Variations of machining force are in this case not great, obtained surface roughness is the least, but these chips occupy the greatest volume and are most difficult to remove.

Chips are seldom present in the form of one of kind mentioned above. Usually, we have to do with intermediate form. The occurring forms of chips are classified in the standard PN-ISO 3685. Fig. 5.18 contains the form of chips in groups tabulated with respect to convenience of removing them from the zone of machining, or not.

Generally short chips are preferable. Besides of machined material property, the tendency of chips to winding and breaking are caused by the conditions of machining. And so, for each shape of tool insert, there can be defined diagram of breaking chips, that is the range of feed and depth of cut, by which the chips possess advantageous form. To take advantage of this range is however not always possible and favorable. Hence, to make the chips of considerable length suitable to off take the machining area, they must be on place chopped up. To this end, there are used separated chip breakers attached to the rake face, or (more often) complex chip-breaking patterns may be incorporated into indexable inserts. In case of materials especially ductile (e.g. the ARMCO iron), when the chips breaker do not bring the desired effect, there are used special systems of tool vibration in the feed direction. Matching the frequency with this vibrations to the rotational speed of subject (or the tool) and their amplitude to the feed value there are obtained partial chips, which are easy to removal [6], [31].

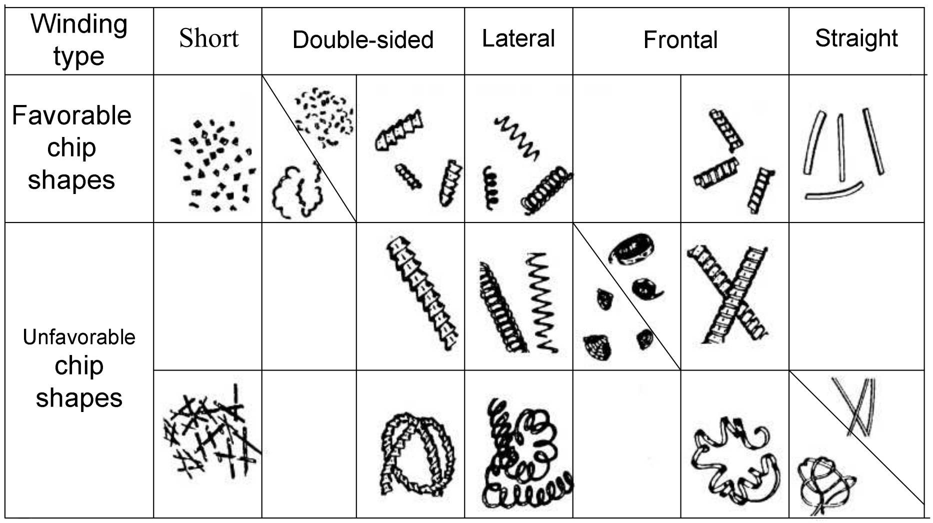


Fig. 5.18. Classification of chip shapes from the point of view of their suitability

Additional flushing of the part, the fixture and pallet with a stream of coolant may assist chips removal from the workspace. With the use of conveyor, chips are conveyed to container, or with help of transport system (also mostly of conveyor-type) beyond the production area (Fig. 5.19). Because of safety measures, and to avoid disturbing the access to the working stands, the conveyor is placed under the floor of the production hall, as shown on Fig. 5.19.

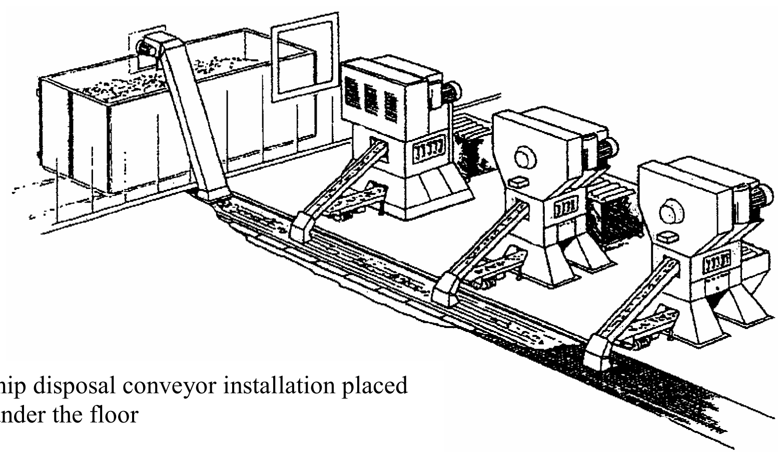

Fig. 5.19. Chip disposal conveyor installation placed under the floor

Placing the chips conveyors under the floor of building decreases however the flexibility of FMS structure. Spacing the workstations is then dependant of the access to the conveyor.

Another system, which does not show these faults, is suction of chips and conveying them by the installation of compressed air. (Fig. 5.20).

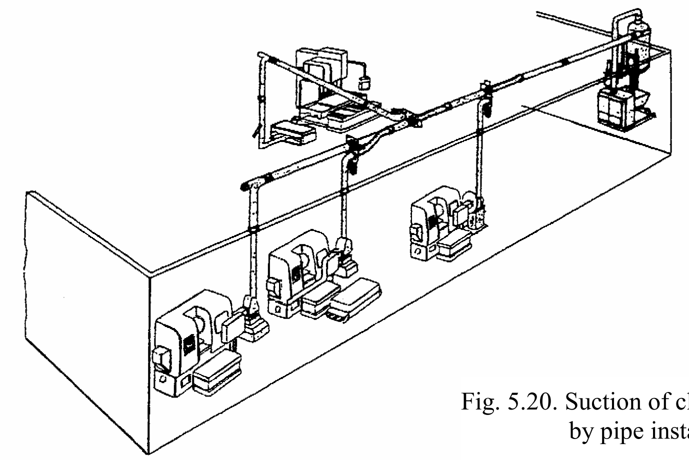

Fig. 5.20. Suction of chips and transport them by pipe installation

Chips, before sending them as a scrap metal are subjected to initial processing. This is realized in special chips workstation. This includes the following:

- Crusher to chopping up the chips,
- Centrifuge to drying the chips,
- Briquetting machine.

Crushing the chips is aimed to decrease their volume making transport easier and further proceeding. The need to clean the chips out of the coolant is caused by many reasons [27] and so:

- There are to be gained considerable amounts of machining liquid (especially oil as its constituent) which can be used again; chips contain 8% of the whole capacity of coolant used during processing,
- The weight of chips is decreasing (essential because of transport costs); (in the slime left after grinding there is 40 to 45 % of liquid.
- The procedure fulfils the requirements of environmental protection, because cutting fluids getting out of chips stored on open air may penetrate to the soil and water causing pollution.

Briquetting does to decrease the capacity of chips in a radical way, meaning significant simplification of storing and transport, thus decreasing the associated costs.

# 6. CUTTING TOOL AND TOOL MANAGEMENT

Generally, the aim of tool management system is:

*Getting the right tool to the right place at the right time*

Having an acceptable tool management system to fulfill the tooling requirements of an FMS means adequately addressing the following problems:

1. Determination of the total number of tools required for the system to process the previously defined FMS part spectrum and system work time,
2. Assignment to each tool of a data set: tool number, exact tool dimensions (contour and angles), remaining tool life, recommended cutting parameters,
3. Storage of suitable numbers of tools at the machining center,
4. Delivery, when needed through an AGV, tools from central FMS store to machine tool,
5. Suitably rapid tool changing during part machining,
6. Tool monitoring and perform adequate action by disturbances.

The right realization of above-mentioned activity should be reflected in the design and control of particular machine tools, in solutions used in transport and storage systems, as well as in the organization of the whole FMS and its management. All these problems are defined as a *tool management system*. The tasks of this system in association with data gathering and processing are presented on Fig. 6.1.

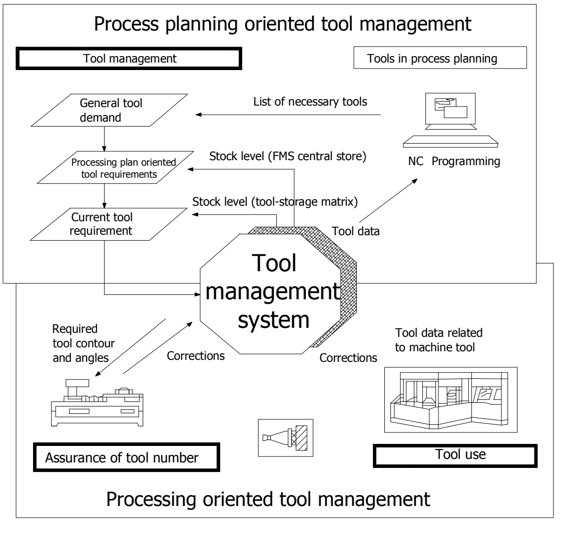


Fig. 6.1
Tasks of tool management system in FMS

Because of range of collected information, they are presented in two groups:

- Process plans oriented,
- Processing oriented.

The first of these groups covers information necessary to keep the state of tools in the manufacturing system necessary for realization of all accepted orders defined by accepted part technology plans.

## 6.1. DEFINING THE TOOL DEMAND IN FMS

The most important in the group *process plans oriented* is problem of defining the tool demand for manufacturing system. It is determined by the following factors:

- The length of manufacturing cycle,
- The number of part batches,
- The main time quota,
- The mean tool life.

Fig. 6.2 presents an example of structure of demand for tools on a stand-alone automated machine tool.

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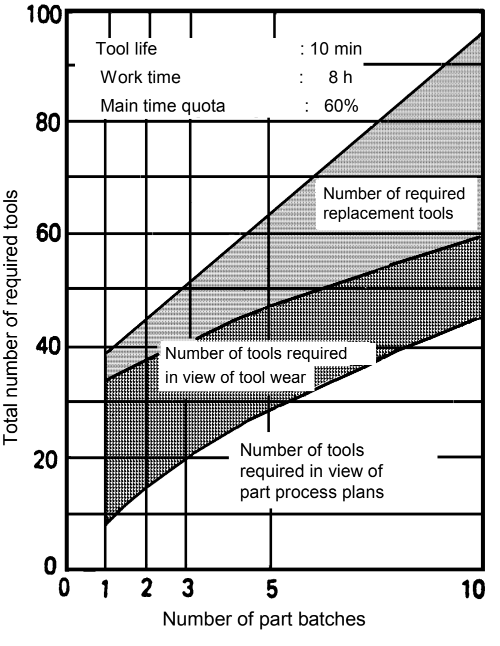



Fig. 6.2. Structure of the cutting tool demand in automated manufacturing

The total number of needed tool is the sum of:

- Number of tools required from part process plans point of view,
- Number of additional tools due to their wear,
- Number of replacement tools.

The first from among these numbers consists of various tools necessary to carry out the process of complete part machining, whereas the tools of each kind is represented in this number by one piece.

Depending on the frequency of taking part in the manufacturing process there occur differences in demand for tools of particular kinds resulting of their wear. They define the second of mentioned numbers. Analyzing the collection of tools necessary in the system with consideration of their wear, one can notice, that some of them are presented during machining very often, while another only once. Therefore, the demand for similar tools of the same type is great by machining only one batch, whereas the increase of this demand diminishes together with the increase of number of batches and with variety of machined parts.

The collection of replacement tools consists of additional pieces of these tools, which in the process of machining of a whole part spectrum are used so seldom, that in the principle, there are enough in the magazine to have only one example of each of them. However, in case of failure associated with damage of such a tool, this threatens to cause a standstill in production. Due to this reason, there exists a necessity to have in magazine a subsidiary tool, “just in case”. The number of tools grows together with the variety of machined parts.

The analysis of diagram, shown in Fig. 6.2, allows formulating the following, general inferences pertaining to the relation of total number of tools necessary to machine a define part spectrum to the variety of these parts:

- The number of tools required in view of process plans does not grow linearly, together with the number of part batches, because tools may be used by the machining of many part batches whereas, the wear of tool can be measured by sensors, or anywhere also – more often – calculated as the sum of cutting times taking in consideration the cutting conditions,
- The number of tools related to their wear is diminished both relatively as well as absolutely, because the frequency of use of particular tools is decreasing,
- The number of replacement tools is progressively growing.

## 6.2. TOOLS USED IN FMS

The essential requirement, which must meet construction of tool used in the FMS, is to ensure the possibility of automatic exchange both, the whole tools, as well as the tool inserts. The second important requirements is minimization of tool inventory with simultaneously ensured possibility to realize all machining purposes on defined part spectrum. The requirements of flexible automation of manufacturing are in the best way reflected by the "tool systems" consisting of such elements as tool holders, adapters, collets, as well as other tool assembly components. Of this, components there can be set various units of tools to suit the needs of technological purposes.

Among the main requirements made to the tool system, there are the following:

- Possibility to make the greatest number of technological operations with the help of tools set out of elements of defined tools system,
- Simplicity to rearrange the system, i.e. short time of tool assemblies buildup and teardown,
- The possibility to use in the system holders and standardized tools,
- High rigidity of tools.

There are distinguished three kinds of tool systems:

- Rotating tool system (tools for milling, boring, drilling),
- Stationary tool system (tools for turning),
- Unified, connecting in itself both the rotating and stationary tools (Fig. 6.3)

The system of rotating tools consists usually of three stages: holders, reducing or extension adaptors, standard tools and tools of the system.

The system of stationary tools consists of holders and connected with them tools fixed in turret heads, or in tool grippers. The best solution in case of normal tool wear, or breakage is to exchange only the tool insert. This principle is used in the tool construction, in which the tool insert is clamped to a separate element, fixed than manually or automatically to the tool holder. This structure bears the name block tool system (the name Block Tool System has been introduced by the firm SANDVIK COROMANT). Significant enlarging the technological possibility of turning centers is obtained thanks to driven rotating tools, fixed in turret heads. The turrets designed to use such tools must be equipped with drive unit usually with a special, independent motor. The tool is driven only then, when the tool is in working position.

There were also elaborated unified tool systems (e.g. by the firm KENNAMETAL - U.S.A. and KRUP WIDIA - GERMANY) containing both the stationary, as well as rotating tools.

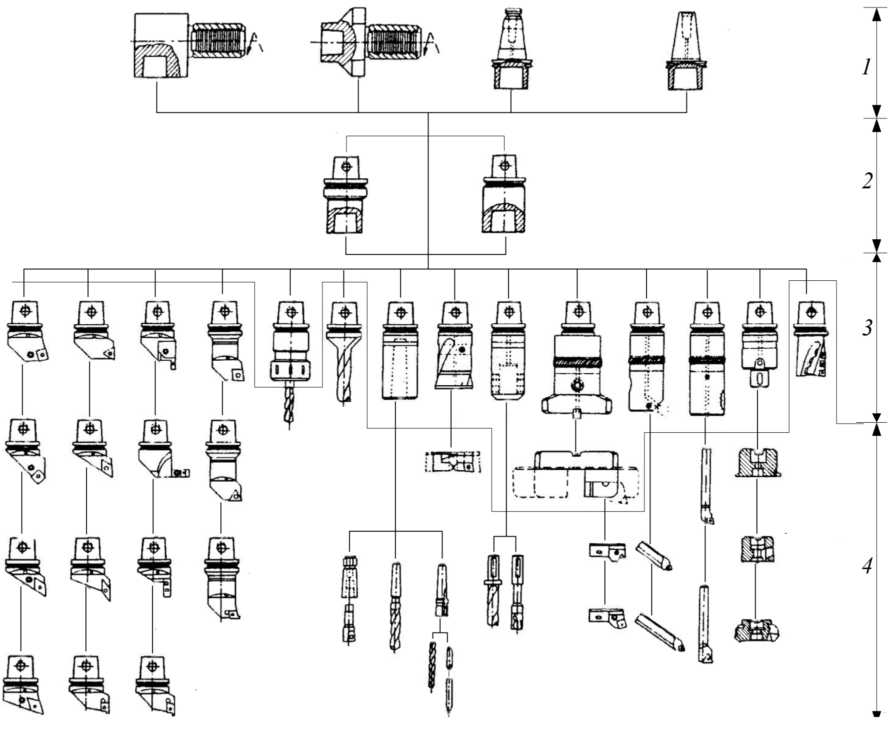



Fig. 6.3. Unified tool system: 1 – master shanks, 2 – reducing or extension adaptors, 3 – holders, 4 – standard tools and tools of the system

A separate group of tools is special tool systems and special tools designed for defined technological purposes. Most often, these are systems of boring tools, boring heads with independent feed of cutting edge, and special heads for simultaneous milling, or boring of several surfaces. An interesting solution of special tool is a head for precision boring of the firm KOMET [12] (Fig. 6.4). It enables the automatic correction of diameter of machined hole during operation. The head is adapted to work at rotation speeds reaching 7000 rpm! Precise resetting the slider with the cutting part of tool with the use of integrated motor with the head, may take place up to the speed of 3000 rpm. The accuracy of resetting the slider is $10^{-3}$mm within the range of 0-2mm. The motor is remotely supplied by induction current. This is realized in this way that at the side of the machining tool (stationery), there is the coil of the stator (inducing) supplied from the network, whereas at the side of rotation there is the coil of the rotor, delivering stabilized, steady voltage to the head. Feeding is activated only in the time of resetting. Data transfer realizes an infrared sending/receiving interface, connected with a control computer (PC) and CNC of the machine tool. On the head circumference there are six sending/receiving modules, what ensures the data transfer in each tool angular position. To determine the value by which should the position of slider be corrected, the machined hole must be measured.

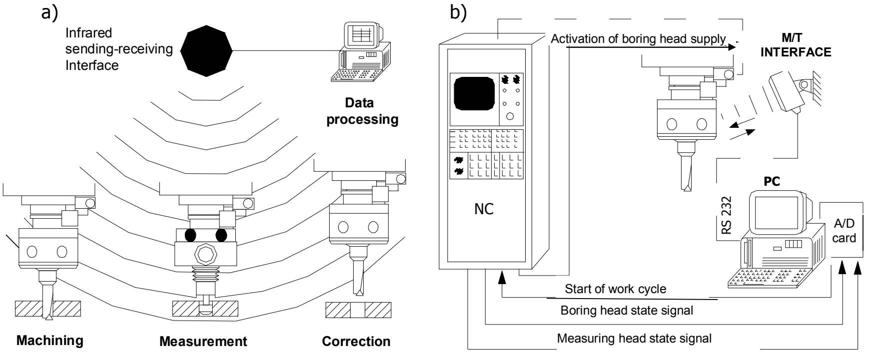



Fig. 6.4. Head for precision boring with automatic dimension correction:
a) working principle, b) control system

To this end an interchangeable gauge plunger is used, provided with a measuring system, a feeding system (battery), system of bilateral transferring of signals (also in infrared range), and integrated system of conversion the measuring signal. The end piece of the measuring gauge plunger defining the value of a given dimension is interchangeable and thanks to it may be used to measure the holes of various diameters.

## 6.3. TOOL PRESETTING

The most important data, which must be specified to each tool used in flexible manufacturing system, are its real dimensions. The necessary constituent of FMS is than the tool presetting station on which measurement of tool is carried out, after buildup of tool assembly, and also after changing of tool insert, or after sharpening [7] (Fig. 6.5). Previously, the arrangement for measuring tools, were based on mechanical dial gauges, or also on the use of micrometer screws for setting up the measuring structure (combined with a crosshairs) with respect to contour of measured cutting edge on the focusing screen. The measuring activities were carried out manually similarly as by feed, using the keyboard, the measurement data, into DNC computer, or into MCU. The micrometric screw has been then replaced with incremental measuring system, which allowed on the one hand using digital displays and on the other hand to get numerical signals suitable to computer processing. Currently there are used the presetting machines based on touch-readout tool gages. Readout information is then recorded either manually or electronically for inputting to the MCU when the tools are loaded and ready to manufacturing duty.

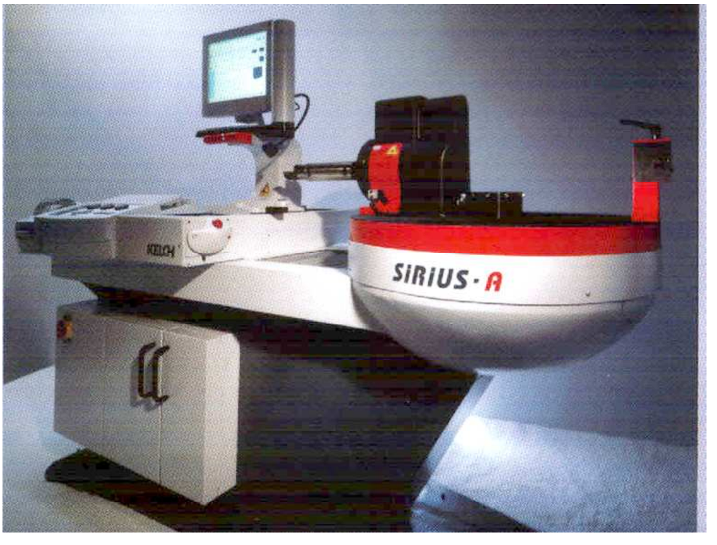



Fig. 6.5. Tool presetting machine

The presetting station is provided with computer, which besides of supporting the measurements activities fulfils the task of tool management in the manufacturing system. Besides of manually operated, there are also offered full automated, CNC controlled, presetting systems which enable unmanned operations. They do not only automatically call the measurement programs for each tool and processes and further transfers measuring data. In the memory of computer, there can be stored measuring programs of all tools used in the system. The results of measurements can be transferred to DNC computer, directly to the

MCU, or recorded on a microchip embedded in a sealed capsule that can be inserted in the tool holder.

The results of measurements of tool, before sharpening may be used directly to control the tool grinder. A presetting machine of the firm ZOLLER (Germany), specially adapted to sharpening the tools, enables the direct transfer of suitably processed results of measurements for practically optional system of control the grinder [18].

## 6.4. TOOL HOLDERS

Tools are mounted in the machine tool in *tool holders*. The connection machine – cutting tool is one of the most important mechanical interface in the manufacturing system and therefore there are high requirements to the following factors:

- Concentricity of the tool and the spindle (ref. to rotating tools),
- Accurate axial tool location,
- Unambiguous orientation of tool cutting edge,
- Stiffness,
- Secure clamping,
- Ease of ejection,
- Effectiveness of torque transmission,
- Cleanness of location and clamping surfaces,
- Possibility of coolant delivery direct to the cutting edge.

For rotating tools, tool holders typically have a tapered shank that fits into a matching tapered hole. The most tool holders designed for rapid, automatic tool change have a steeper taper (such as 7:24, of mostly used size 40, 45, 50).

Fig. 6.6 shows a standardized tapered shank of tool adapted for automated systems of manipulation and storage. The axial position of tool is fixed on the tapered surface. The tapered connection possesses a range of advantages. By clean taper, there may be obtained the accuracy of location the tool after its change ensuring the allowance of the diameter of machined hole even in the range of 0.002 - 0.003 mm. Whether independently of the driver, the friction on the taper allows to transmit about 20% of the whole torque. A disadvantage is that in high-speed machining the centrifugal force opens up the seat and the grip on the tool holder loosens. This caused that tool fixing force pool the tool holder into seat of spindle, which lead to its seizure by tool changing (Fig. 6.7).

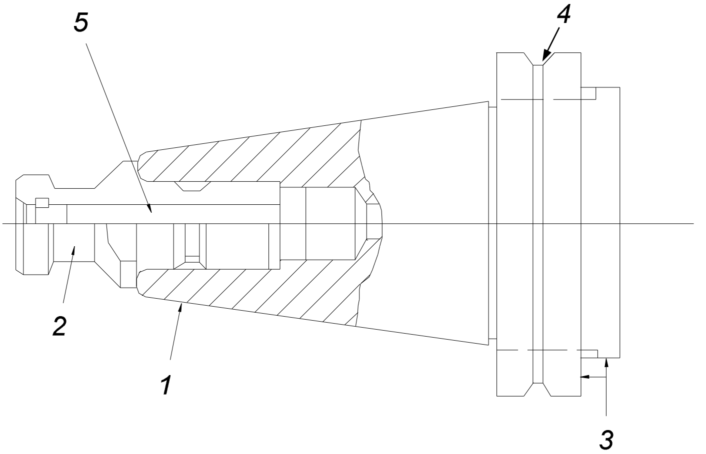



Fig. 6.6. Steep taper shank for rotating tools: 1 – tapered base surface, 2 – tool tang, 3 – tool centering and fixing surfaces, 4 – grip for tool changer, 5 – hole for coolant flow

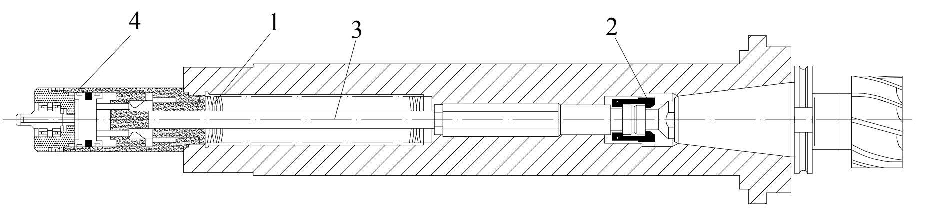



Fig. 6.7. Fixing of tool in the seat of spindle: 1 – set of disk spring, 2 – jaws fixing the tool, 3 – piston rod, 4 – hydraulic drive

To avoid this disadvantage there have been designated a solution with a gripping part of hollowed deformable short taper or with roll shanks (one or two-stage). Broader application has found a cup-shaped holder patented in Germany (DIN 69893) as so-called HSK (Hohlschaftkegel or Hohlspannkegel) (Fig. 6.8) [40], [43], [44]. The procedure of fastening the tool, using the HSK holder, is shown on Fig. 6.9. The basic surfaces are in this case: the taper surface and the face surface in which after the strain of the hollowed taper, tool holder is tightened. This makes it possible to avoid pulling in the tool holder and at the time increasing the rigidity of fixing with respect to the holder with the 7:24 taper.

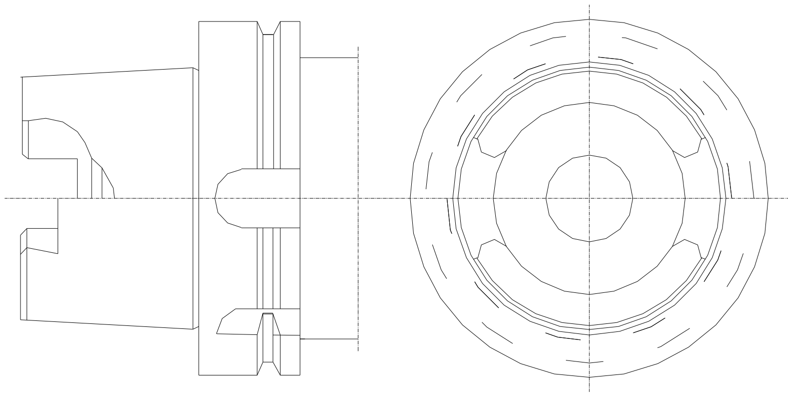


Fig. 6.8. HSK holder for rotating tools

The use of plate springs to clamp the connection of tool with the spindle ensures right fixing even in case of lost pressure in the hydraulic system.

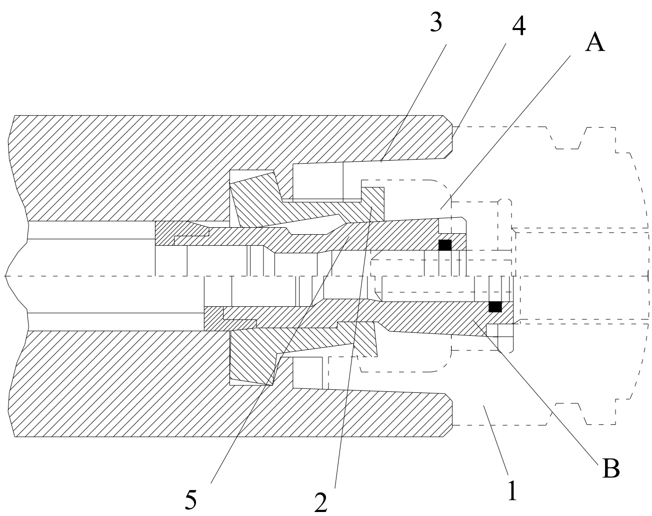



Fig. 6.9. Tool fixing using the HSK holder: A – position of elements in the state of fixing the tool, B – position of elements by connection loosening, 1 – HSK shank, 2 – elastic sleeve, 3 – taper, 4 – connection flange of tool adapter, 5 – elastic pin

The basic requirement to assure accuracy of tool changing is to keep clean the surface of seat and tool shank during changing. Surfaces are cleaned by a stream of compressed air delivered through a system of channels made in the body of spindle unit (Fig. 6.10).

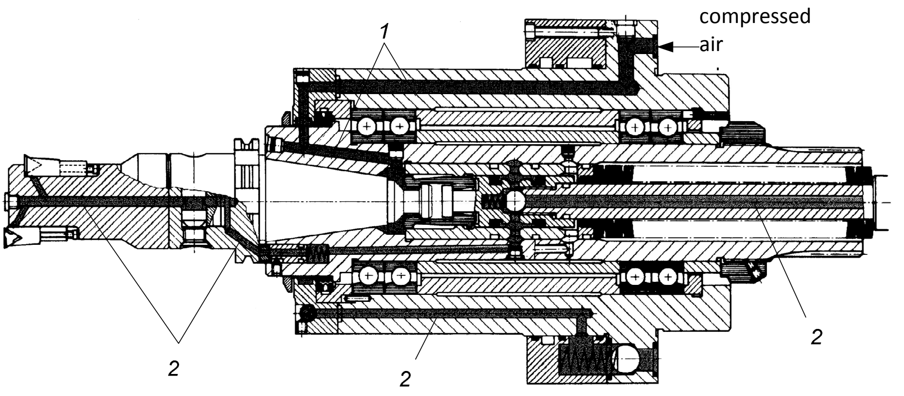



Fig. 6.10. System of fixing the tools with access of compressed air to clean the connection area: 1 – delivery of compressed air to the tool seat, 2 – delivery of coolant to the cutting edge

When placing the tool with taper shank, the gap between the edge of hole in the seat and the taper of shank changes (is decreasing) steadily. This causes increase of air stream velocity and improves the effectiveness of blowing the connection.

The coolant is delivered to the cutting area through the system of channels made in the cone shank and in the spindle body. (sees Fig. 6.10). Besides, of machine-tool connection, an important feature, due to accuracy of machining, is the connection between the component modules of tooling system. In this case, there are no standardized constructions, while the manufacturers of tool systems apply various design solutions. The most important requirements made to this construction, are the following [55]:

- To make right concentricity of tool elements to be connected (accuracy when changing, below 0.005mm on the diameter),
- To ensure accurate axial location and angular orientation,
- Fixing with suitable stiffness and strength.

## 6.5. TOOL MAINTENANCE IN FMS

The procedure of using the tools during the manufacturing process can be depicting in the form of two closed cycles (Fig. 6.11) [16].

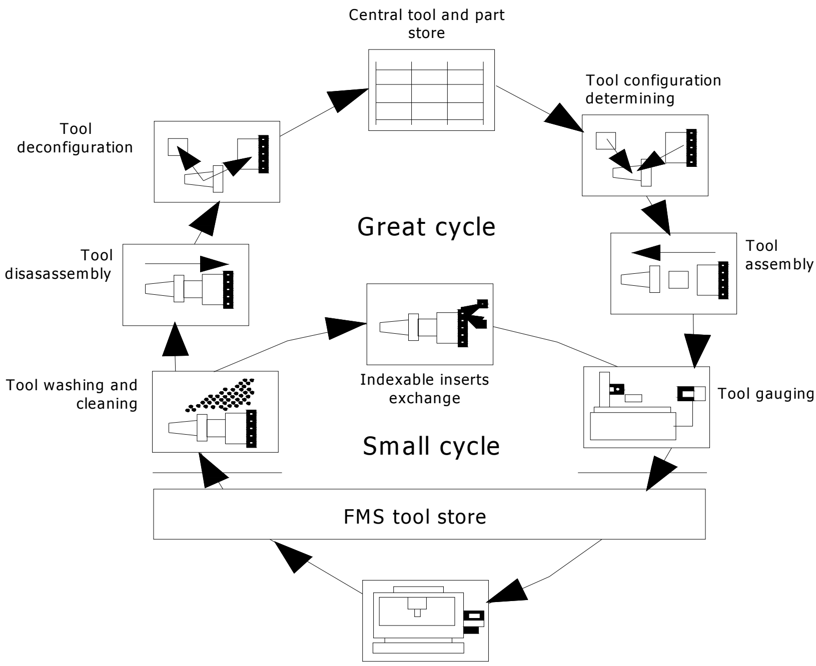



Fig. 6.11. Tool maintenance cycles in flexible manufacturing system

The *small cycle of tool maintenance* is associated with normal tool wear, and with the necessity to exchange the inserts. The tool is removed from tool magazine, and then washed and cleaned. After insert changing, there are introduced new tool geometry data, on the presetting station. Following these procedure, tool returns to central tool store of FMS.

After fulfilling machining of the whole ordered part batch, the tools are washed and teardown, and then, their component elements are placed in a central store. In accordance with the part program requirements of the designated part spectrum for a given production run a new set of tools for the next production period must be accurately prepared. After building up of new tool assemblies, they must be setting up and completing the geometric data. Then they are placed in the FMS tool store. This is the so called the *great cycle of tool maintenance*.

## 6.6. INTEGRATED TOOL STORES

In the course of development of flexible manufacturing systems, there were originated many design solutions referred to tool stores, integrated with a machine tool (tool magazines, tool matrices). There are two groups of integrated tool stores:

1. With variable tool position – active, delivering of tools to changing place takes place through movements of tool matrix,
2. With stationery tool position – passive, required auxiliary devices delivering tools to the changing place.

The first ones possess drive and as a rule are equipped with tool changer, if the function of changing is not realized without the changer (pick-up method). There are most often used stores (especially in chain and disk execution) in machining centers. Among the constructions of stores with variable tool position, may be mentioned three basic types: disk, chain and tower types. Diversification of main design features among these types is shown on fig. 6.12 (according to [55]).

This diversification is referred first to the position of tool axis with respect to the axis of tool matrix rotation, which may be parallel, rectangular, or tangent. To the commonly applied design, there belong the following:

- Disk stores with tools positioned parallel to rotation axis (Fig. 6.13); they are used both in centers with vertical, as well as with horizontal spindle axis, especially on case of pick-up solution,
- Chain stores with tools positioned both in parallel as well as perpendicular to the tool-storage matrix rotation axis.

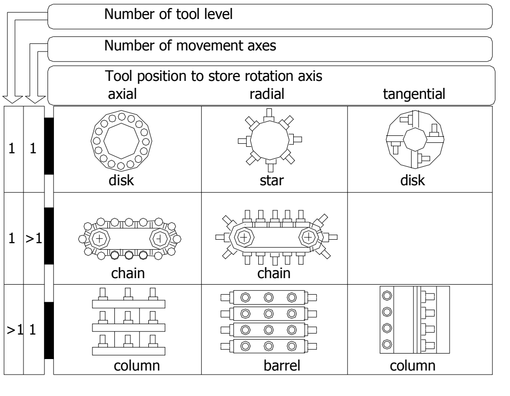



Fig. 6.12
Types of integrated tool stores with variable tool position

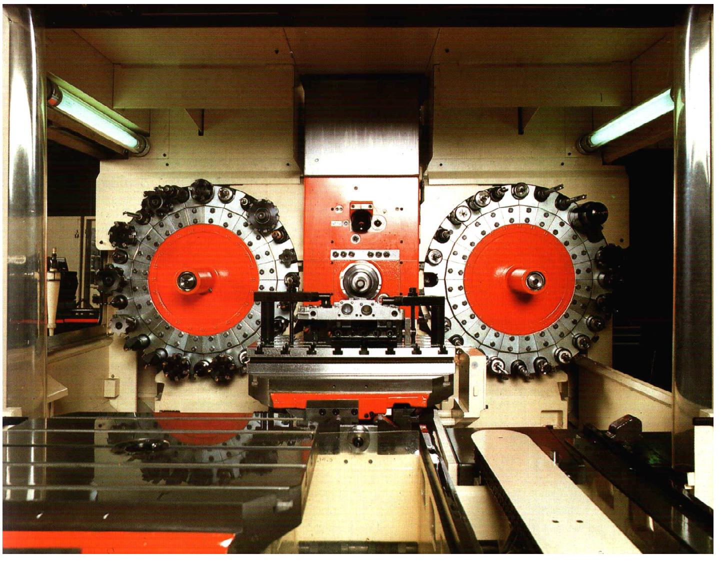


Fig. 6.13. Machining centre with two disk stores and pick-up tool changing method

The tower stores are seldom used (e.g. by firm HECKERT [67]); their disadvantage is, that they require an additional device delivering the tool to changing position.

Stores with stationery tool position require a manipulator, or a robot. They are used in machining, as well as in turning centers. The basic types of designs of these stores are shown on Fig. 6.14.

There can be distinguished three basic types of stores: one-dimensional (linear), two-dimensional (pallet, cassette) and three-dimensional (stillage).

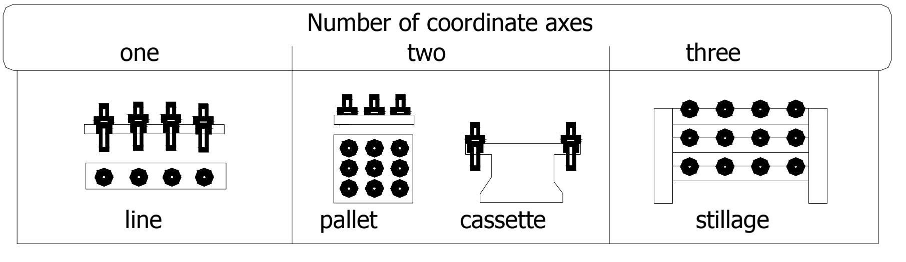



Fig. 6.14. Types of stores of with stationery tool position

Linear stores are used as rectilinear (used e.g. in turning centers), and as ring-type. An example of stationary ring store is its application in the machining centers FZ08 & FZ12 of CHIRON [36], where tools are located in form a ring on the spindle. The store remains immobile, while each tool has an individual changer.

The two-dimensional stores are met as pallet and cassette stores. The latter are easy to change the capacity and quick tool exchange through the exchange of whole cassettes with a set of tools [69], [70].

The stillage stores are mainly used as central stores of tools of flexible manufacturing system (e.g. in systems of WERNER [73]).

## 6.7. TOOLS CHANGING AND EXCHANGING

During the operation in FMS, the tools must be automatically changed with reference to the realized manufacturing process, and they must be in case of need exchanged in the tool matrix on the machine (Fig. 6.15).

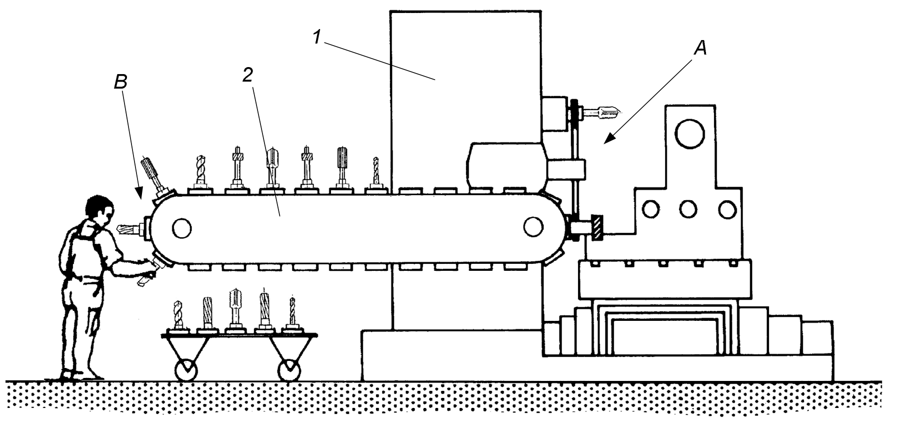



Fig. 6.15. *Changing* of tool in the machine spindle – A, and *exchanging* of tool in the tool-storage matrix - B: 1 – machining center, 2 – tool matrix

As opposed to *changing* the tool what is made automatically, *exchanging* is often made manually by those who service the system. In case, when number of tools in tool matrices is not enough to operate during the unmanned shift, there is however, the necessity to automatize this function also.

## 6.7.1. METHODS OF TOOL CHANGING

Due to increasing cutting speed, causing consequently shortening of machining main times, the share of times of tool changing in the whole time of part machining is increasing and becomes important factor defining the effectiveness of the manufacturing process. The time of changing counted "from chip to chip" that is from finishing the machining by one tool to continue by the next, becomes then a significant factor of technological values of automated machine tools. There are being undertaken actions leading to minimization of this time.

The whole cycle of tool changing consists of the following stages:

1. Selection in the magazine a tool which should enter in operation, delivering it to the place of changing and appropriately positioning,
2. Changing the tool,
3. Delivering the tool, which finished its work, to the magazine.

The time of realization of this cycle depends first from the second stage of tool changing, because the first and the third stage can be realized during the machining main time. If however the operation of machining remains shorter than the second stage of the cycle, then the first and third stages influence then overall time of tool changing.

There exist many design solutions of tool changing. They depend on:

1. The machine tool construction, including:
   - Position of spindle axis (vertical, horizontal),
   - Number of spindles,
   - Number of NC axes in which the tool is fastened (fixed head stock, support, head),
2. Construction and location of tool-storage matrix.

There are two solutions of tool changing:

- Without changer: tool change takes place through movements of tool-storage matrix and machining center headstock,
- With changer: tool-storage matrix movements deliver tools to change place and then changer realizes tool change.

The solution "without the changer” is simple in design. To change the tools, the numerically controlled translation motions of stand with the headstock and tool-storage matrix are used. On the Fig. 6.16 there is shown the process of tool changing in the machining center of the firm HÜLLER HILLE (Fig. 6.13). The sequence of motions is in this case the following: the tool being changed is taken by the matrix, making the translatory motion (1), in turn, the stand makes a motion (2) with simultaneously grip loosing, in this way the tool is removed from the seat in the spindle, the tool-storage matrix makes a rotation (3), placing the new tool in position of changing, the stand makes a reverse motion (4), putting the tool in the seat, then the matrix returns to its primary position (5), and the process of tool changing is finished. In case, when the headstock with the stand possess three degrees of freedom, the translation movements of the tool-storage matrix are unnecessary.

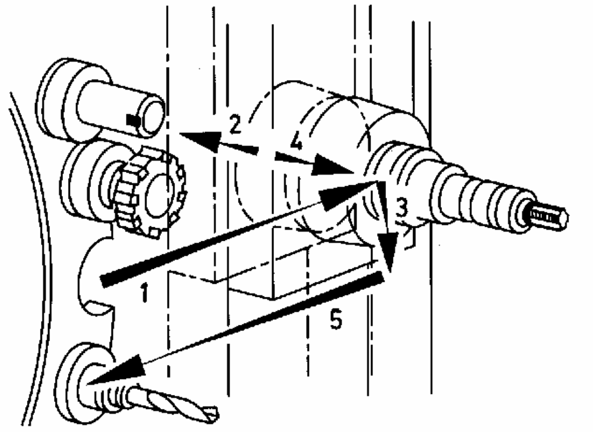



Fig. 6.16. Automatic pick-up tool change: 1, 2, 3, 4, 5 – sequence of headstock motions during the tool changing

The tool changing with the use of "pickup" method allows avoiding complicated mechanism of tool changer, increasing in this way the working reliability of the system. The disadvantage of this method is however relatively long time of tool changing. The whole time consists namely of:

- Time to bring the headstock to changing position and placing the tool which finished the work in a free pocket in the tool-storage matrix,
- Time to select the new tool, i.e. to bring the tool-storage matrix to position in which it will be possible to take the tool to placing it in a seat of the spindle,
- Time to return the headstock to the workspace.

The elimination of a changer is associated with the possibility of better use the tool matrix capacity, because the tool is taken from the matrix pocket in the direction perpendicular to its axis. This enables placing the tools of smaller dimensions between the tools with bigger diameters (Fig. 6.17).

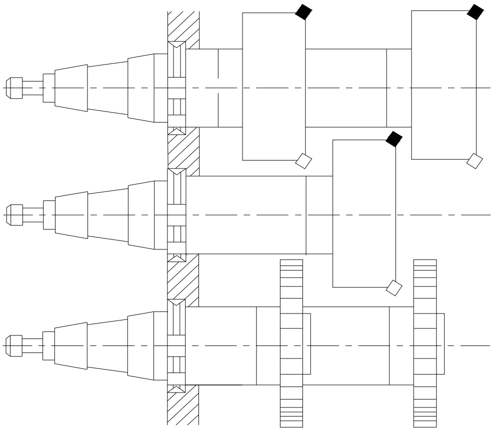


Fig. 6.17. Arrangement of big overall dimension tools

Currently more often is used changing the tools with the use of a changer. The simplest design presents the *single grip changer*. However, due to this fact, that the actions associated with changing the tool must be in this case made in sequence, time of changing is relatively long. That's way double-ended indexing tool change arm is most often used. It enables simultaneously making the actions of changing the tool in the seat of spindle and in the pocket in tool-storage matrix (Fig. 6.18).

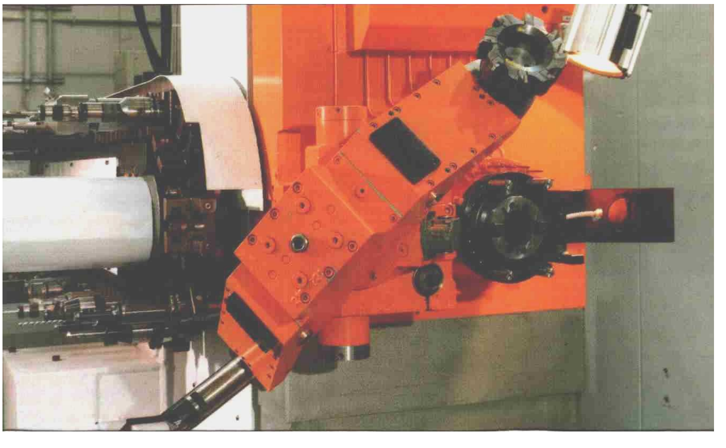


Fig. 6.18. Double-ended indexing tool change angle arm

Although the double-ended, 180-degree indexing arm continues to be the most popular approach, various design of the tool gripping and clamping will vary among builders. To enable movements of grip, there are used various types of driving gears: hydraulic, pneumatic, numerically controlled electric motors, and also cam mechanisms. The last ones possess the most advantageous operation properties. They distinguish themselves by a low price, fluent movements, short time of changing, simple controlling and great working reliability. The time of changing cycle depends on the mass of tool and of the distance of grip jaws axis.

The basic condition, which must be fulfilled by the cycle of automatic changing the tool, is selection the tool, carrying it to changing position and giving back to tool-storage matrix. All these movements are to be realized during the process of machining without interruption the operation.

The development of machining with very high speeds (HSC – *high speed machining*) creates extreme requirements to the quick action of tool changers. In the vertical machining center FZ08 run by the firm CHIRON [36] they applied a solution allowing to obtain the changing time “from chip to chip" equal to 1.5s, and the action of changing the tool alone lasts 0.5s. Such a short times were obtained thanks to placing the tool matrix around the spindle and providing each tool with own changer. (Fig. 6.19). The changer remains during the machining at the tool only the jaws of a grip are open. With such design, the store capacity is limited (in case of FZ08 center, up to 12 tools).

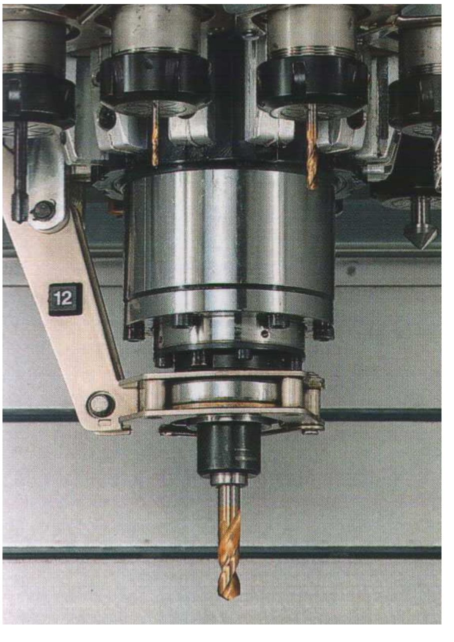



Fig. 6.19. Individual tool changers in vertical machining centre

## 6.7.2. METHODS OF FEEDING INTERGRATED MAGAZINS WITH TOOLS

Methods of ensuring the number of tools necessary for unmanned machining of a wide part spectrum may be generally divided into two groups (Fig. 6.20):

1. Enlarging of the integrated magazines capacity,
2. Automatic tool exchanging in the magazine.

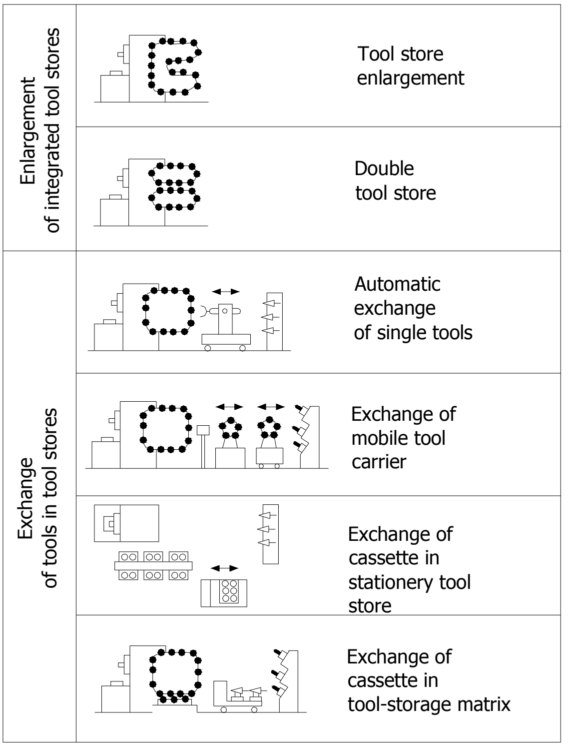



Fig. 6.20. Methods to augmentation of available tools number in magazine

The first group encloses such actions as the enlarging the capacity of store:

- Extension of chain in the chain magazine (Fig. 6.21) or using the easy to augmentation cassette store,
- Multiplication of the number of magazines integrated with the machine tool: e.g. already mentioned (Fig. 6.17) machining center nb-h 70 of HÜLLER

HILLE equipped with two disk stores (Fig. 6.22.a), and, optionally in automatic store changer (Fig. 6.22.b) having three additional stores [69].

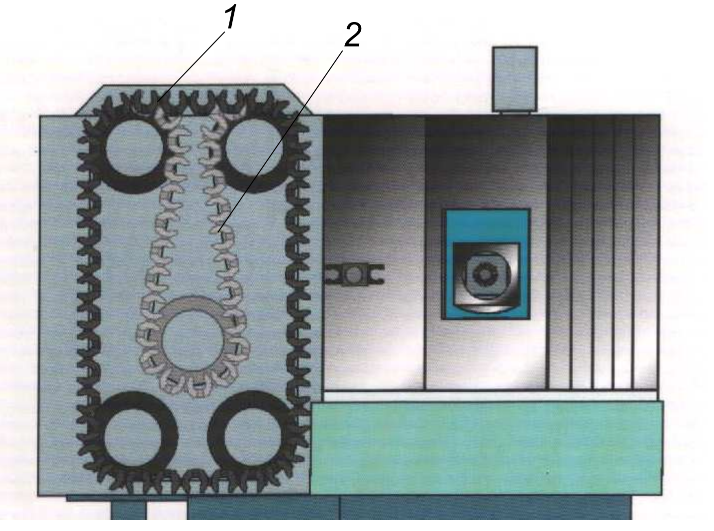



Fig. 6.21. Enlarging of chain store capacity by the augmentation of chain length:
*1* – 60 tools store, *2* – 90 tools store

*a)* *b)*

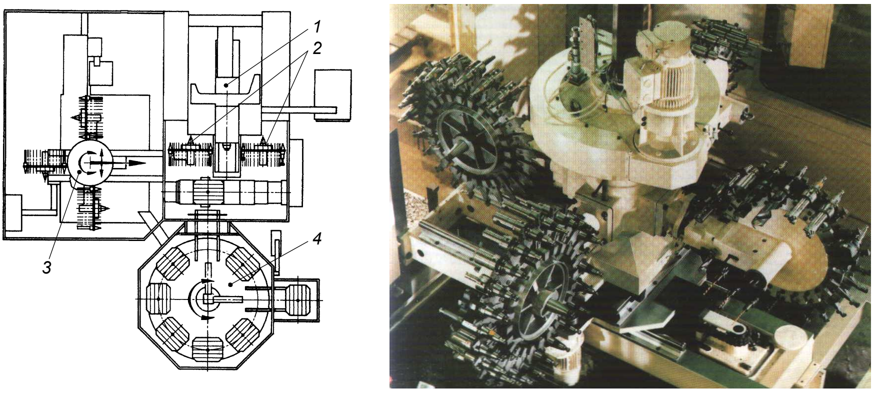



Fig. 6.22. Single NC machine cell with two main tool stores a) cell layout:
1 – machining centre, 2 – tool stores, 3 – three auxiliary tool stores with tool-storage matrix changer, 4 – work pallet carrousels store, b) view of automatic tool store changer

- Providing the machine tool with integrated, stationary main store of great capacity and a movable auxiliary store from which the tools are taken for changing. A linear robot delivering tools to the auxiliary store services the main store.

Such a solution was used in the turning – milling center HEYNUMAT 35 of HEYLIGEN-STAEDT (Fig. 6.23) [33]. In case of this center the main store can have a capacity, optionally 48, 96, or 144 tools. Thanks to the movable auxiliary store, the time of changing does not depend on the length of machined part (max 6000 mm) and is 4s.

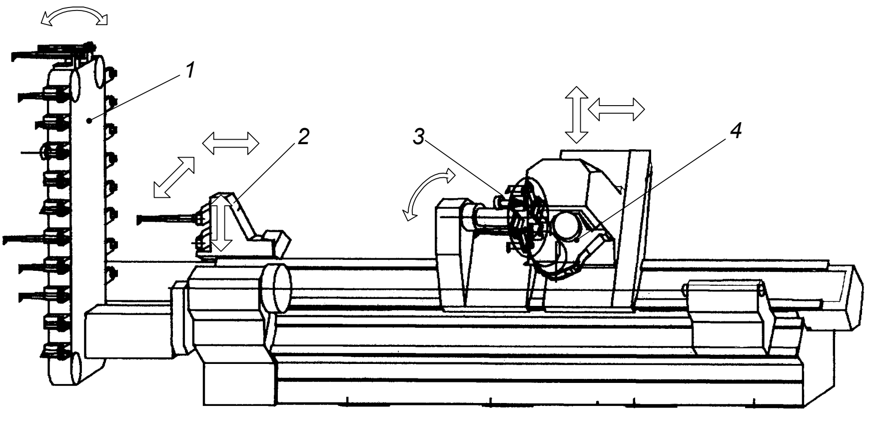



Fig. 6.23. Turning and milling centre equipped with two tool stores; the main – stationary and movable – auxiliary: 1 – the main tool store, 2 – linear robot, 3 – auxiliary tool store, 4 - tool head

The second group of methods to ensure provision of a machine with necessary tools is the exchanging tools, in case of need in integrated magazines. Such exchanging may be realized in various ways. Among the methods most often used are the following:

- Exchanging single tools - may be made either manually or automatically; in the second case, the tools are transported with the help of a AGV from the central tool store to the machine tool and exchanged according to a program [49], [25],
- Exchanging the sets of tools with the use of special multi-tool cassettes may be also made manually or automatically (solution QTC of WERNER [74] – Fig. 6.24.

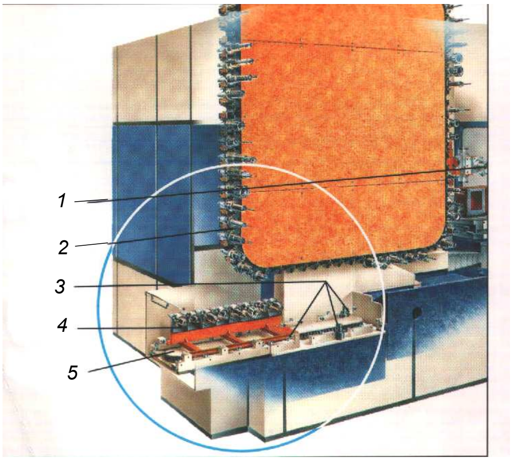



Fig. 6.24. Exchanging the tools in tool-storage matrix using multi-tool cassettes:
1 – tool changer, 2 – tool store, 3 – cassette jack, 4 – eight-tool cassette,
5 – device automatically shifting the cassette

- Exchanging the cassettes in a stationery cassette type magazines; can be realized both manually (Fig. 6.25), as well as automatically [70],


Fig. 6.25. Manual tool cassette exchanging in a tool store with stationery tools position

- Exchanging the changeable disk tool-storage matrix; as an example here is the already mentioned machining center nb-h 70 of HÜLLER HILLE in which has been planned the possibility both manual, as well as using the robot, exchanging the whole tool-storage matrices [69].

## 6.8. TRANSPORT OF TOOLS

Exchanging tools in the integrated magazines is connected with the necessity of transporting them from the central store. It may be carried with the help of service personnel, especially when in the period of unmanned operation there is no need to change the tools or also using the automated transport means. The type of transport depends on the structure of system. Most often, these are the universal transport means, such as AGV with mounted industrial robots (Fig. 6.26).

For transporting of tools, by system with linear structure, may be used the mobile robot servicing the tool store. In the example shown in Fig. 6.27 such robot carries out both the tool exchanging in integrated magazines, as also in the central tools store of FMS.

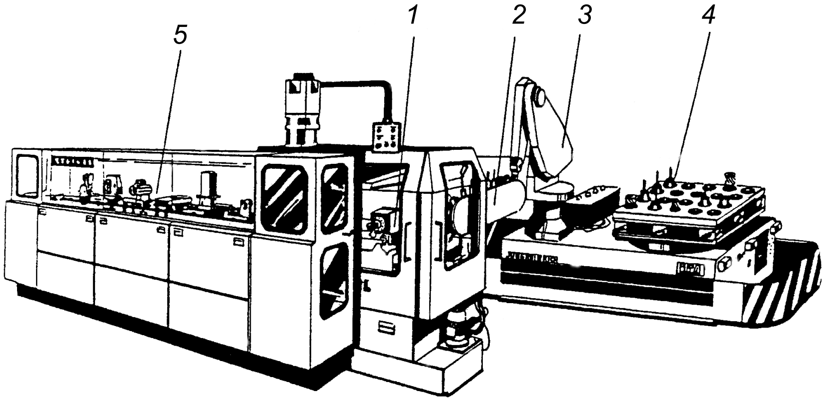



Fig. 6.26. AGV tool transport: 1 – machining centre, 2 – tool-storage matrix, 3 – robotized AGV, 4 – pallet with tools to be exchanged, 5 – work pallet store

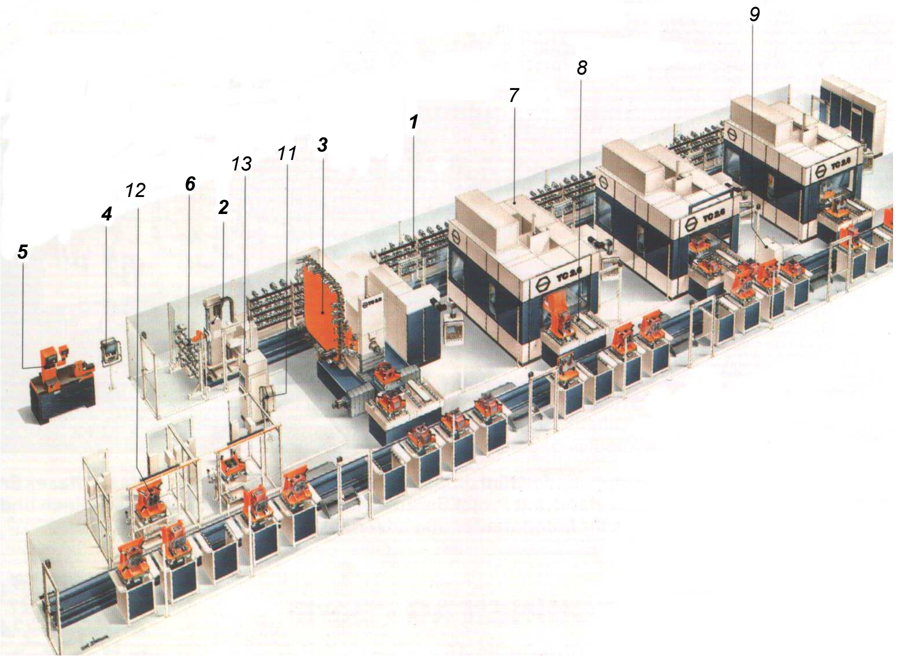



Fig. 6.27. Flexible manufacturing system with the rack-type central tool store serviced by the manipulator realizing the tool transport function: 1 – FMS central tool store, 2 – mobile robot servicing the store and realizing the tool-exchanging task, 3 – tool-storage matrix, 4 – tool transport control, 5 - tool-gauging station, 6 – tool room, 7 – machining centre, 8 - pallet changer, 9 - work pallet transport, 10 – palettes leaving system area, 11 – pallet transport control, 12 – loading parts onto fixture pallet station, 13 – FMS central control

## 6.9. TOOL IDENTIFICATION

To introduce, according to part machining program, into the work appropriate tool, it must be first identified. There is a lot of solutions of this problem. The most common identification systems are based either on the connection of tool with its place in the magazine (then, the program calls for the number of pocket), or on direct tool coding. In the first case, we may have to do with an invariable or variable assigning the place in the magazine, to the tool.

With an invariable assigning, we have to do, when to each tool there is steadily assigned a defined place in the tool matrix. The number of pocket is at the same time the identification number of tool in the part-machining program. This is the simplest solution, but showing also many disadvantages. The main are the following:

- Possibility to make an error by loading the tool magazine,
- Long time needed to change the tool, because by each changing, the magazine must be put in two positions (in place a new one and former tool).
- Problems which appear in case of replacement or sister tools, because in the part machining program there is only the number of place of original tool, whereas the substitute tools are in another pockets.

This way of identification of tools is very rarely used due to disadvantages mentioned above. Its usage can have a place e.g. in turret lathes.

Significantly more advantageous is "the variable assigning the place in a tool magazine". During the operation of a machining center, the tool can be located in any pocket.  By the loading, the tool magazine the number of this pocket is reading in the MCU memory. From this moment on, the machine CNC takes over the function of managing the tools in the magazine and assigning to each tool (marked with a defined number) the place in the store, and other tooling data, such as the tool length, cutter diameter compensation, feed-rate and spindle override information, and remaining tool life. This method of coding does not hinder, maintain - in case of need - steady tool places in the magazine, what sometimes may be very useful when e.g. arrangement of tools in the magazine has been optimized due to their overall dimensions. The difference with respect to the first being discussed way of coding is, that in the program of machining there is given the tool number, and not the pocket number. In both cases, however the tool is not provided with identifier, which would be read by the control system of the machine tool. This takes place in other methods of tool coding, such as the mechanic and the electronic.

The mechanic coding consists in placing on the tool shank certain number of rings, which allow coding the tool number in binary system (Fig. 6.28). The identical tools receive the same numbers.

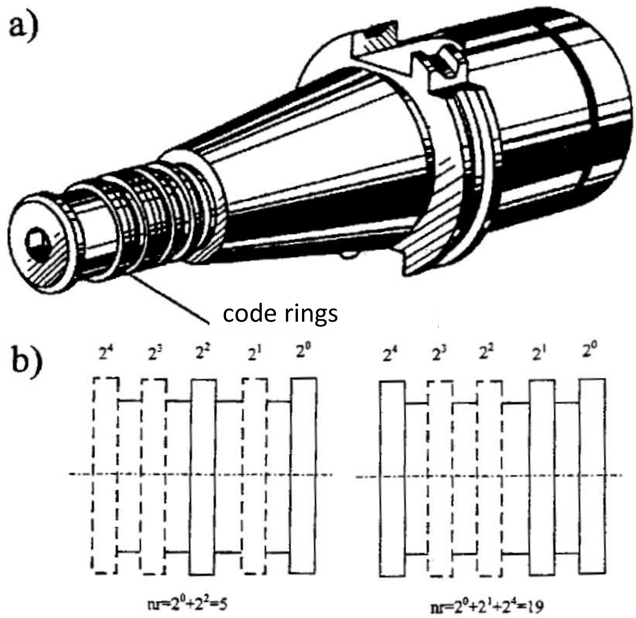



Fig. 6.28. Mechanical (ring-type) tool coding: a) positioning of rings, b) examples of tool number coding

The machine tool is provided with a system of reading the coded in this way numbers and hence the tool may be put in optional place in the store. This method of coding although reliable has however certain number of disadvantages, which are:

- Long time of tool selecting caused by two reasons:
  1. There is necessary relatively low rotation of the magazine due to inertia of mechanical parts of the reading mechanism and apparently danger of faulty reading,
  2. Lack of information about the direction in which should the tool be searched (it may be in the nearest place in the store, but full revolution would be made.)
- Relatively great cost of coding associated with significantly more expensive, because more complex grip of tool and
- Problems appearing with the control of replacement and “sisters” tools which have the same numbers as the original ones.

Significant decreasing of costs does the use of bar coding. This method is the most popular form of automatic identification as evidenced by supermarket checkout lanes and other retail business use. With NC (FMS), bar codes are imprinted on paper or Mylar and fastened to the tool holder with adhesive. That's just is the main disadvantage, that under the action of cutting fluids, the labels easily fall off and the tools lose their identifiers.

The most advantageous is the most commonly used in the last time, the microchip identification. This system employs the use of a microchip embedded in a sealed capsule that can be inserted in the tool holder. The microchip contains a memory, usually with capacity of 1024 bits allowing the user to record 85 twelve bytes letters and can by programmed off-line with the tool identification and other tooling data. Reading can occur with using of a noncontact read-write head that can be attached to tool changers, presetting fixtures, or tool grippers (Fig. 6.29).

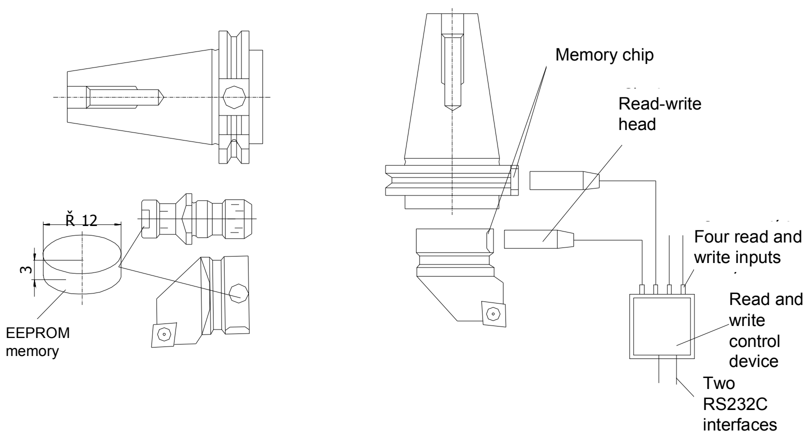



Figure 6.29. Placing of memory chips (EEPROM) in the tool holder by microchip tool identification

Fig. 6.29. Placing of memory chips (EEPROM) in the tool holder by microchip tool identification

When taking the tool out from the magazine the tooling data are automatically actualized, (especially it refers to tool life expectancies). The advantage of this system is shortening time of coding and decreasing the possibility to make error, the disadvantage increased costs.

## 6.10. TOOL MONITORING AND FAULT DETECTION

The tool fault (wear, break, damage because of collision, as well absence or misplacement in magazine) is the most often occurring cause of disturbances in working of manufacturing systems. It is stated, that about 45% of emergency downtime are caused by tool faults [1]. The ability to sense and respond to tool fault conditions is an important issue in FMS tool management. Under tasks of tool monitoring system, the following are the most important:

- To ensure that tool timely (when the tool life has expired) will be replaced,
- To possibly quickly react in case of catastrophic tool failures or collision damage.

The basic method of tool condition monitoring is recording of its cutting time, however determining of cutting edge state is not precise on this basis and usually leads to loses due to untimely putting the tool back in the matrix and marking it as “worn out”, or catastrophic failures before life time is expired. Therefore there are undertaken various trials to watch the progress of the tool wear and to precisely determine its actual condition. The inferences regarding the degree of tool wear are drawn usually indirectly on the basis of measurements of such values as e.g.: cutting force, input power, deflections of machine tool elements, vibrations, acoustic emission, tool length (or diameter), and part accuracy.

When the actual tool life time expires the process of machining is usually not interrupted, but is continued, with the decreased feed by about 15-30%, until the nearest tool change and only then the worn tool is exchanged in the tool storage matrix for a substitution one – automatically, or manually by the service man. In case when it is well known, that by the machining of certain parts some type of tools are so intensively used that the life time of one tool is not sufficient, there must be found “sister” tool in the tool matrix. Then, by the changing the worn tool is suitably coded so, that it could not be taken again from the magazine.

In case of catastrophic tool failure, within 1-3 ms is sent a signal, omitting the CNC, switching off the feed drive; the machining is at once interrupted. The machine tool is brought to a neutral position and pallet with the machined part is exchanged. The worn-out tool is changed by a replace one and the machining is continued but of a new workpiece.

If the tool condition is determined by indirect measurement, then obtaining proper effects requires careful selection of suitable sensor, its location in the system and appropriate monitoring strategy suited to the type of machining, machined material, and first of all, to the monitoring aim.

## 6.11. CONTROL TASKS IN TOOL MANAGEMENT SYSTEM

The control tasks in the tool management system of FMS may be grouped in two areas:

- Directly associated with the machine tool function – they are realized by the MCU,
- Associated with the flow of tools in the whole FMS – they are realized by the host computer, by DNC computer (if such one is present), or tool room computer.

The basic tasks of CNC machine tool control system are monitoring of tool condition (Fig. 6.30) and associated with it managing of the replacement tools (sister tools), in case of wear or collision damage.

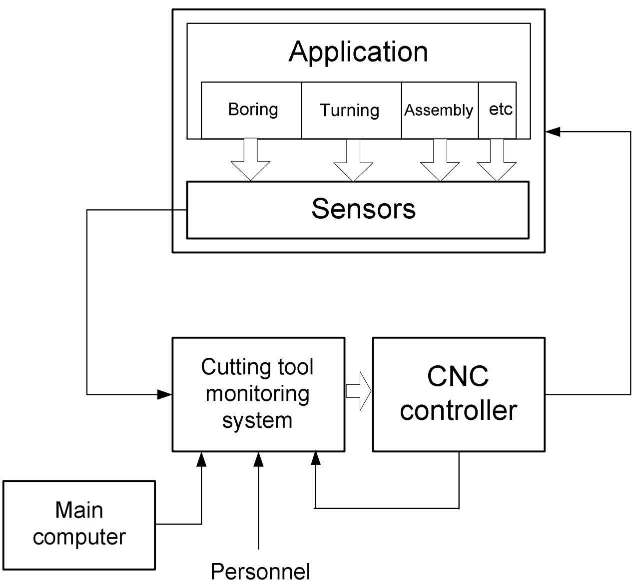



Fig. 6.30. Scheme of tool monitoring control

Besides of this task the CNC control of the machine tool fulfils the task of inspection of the state of tool magazine when rearranging the machine tool from one kind of machined part to another one. When ending the machining of parts series A, and after reading in the machining program for parts series B, there should be prepared a demand for tools necessary for machining this series (B). Realization of this function covers the following actions:

- Checking, which tools are necessary to processing the parts A and B,
- Making a list of tools present in the magazine but not needed to machining the parts B,
- Making a list of tools which are not present in the magazine but needed by machining the parts B,
- Release the unnecessary tools for exchanging,
- Determination (if this is not marked in the machining program) time sections in which tool exchanging in the magazine may be made.

Additionally, there may be made (and handing over to FMS staff) a grouping of tools with the same residue life time. This will make easier organization of tool exchanging allowing at a time to prepare their appropriate number.

In case of FMS with a central control of tooling system, the task of management on a level higher than machine tool realizes a especially for this purpose assigned computer (e.g. tool room computer) or DNC computer.

# 7. PART MANAGEMENT SYSTEM

The right of existence of each manufacturing system is the production of specific products. The machined parts are then in the center of interest by planning, design and using of flexible manufacturing systems. Problems referred to machining parts are divided into two basic groups associated with:

- Planning of system and
- Its composition and use.

In the first case, it refers first to the analysis of part spectrum with which we have to do, in the second case to the optimal part flow through the manufacturing system.

## 7.1. PART ANALYSIS

The main problem by such analysis, and then the task by planning of system structure, can be formulated as follows:

*Determining of the type and number of production means necessary to processing a specific part spectrum.*

It refers both to standard equipment, accessible on the market, as well as to the design of special means (e.g. fixtures, special tools, gripping devices etc.).

The aim by system planning is such a choice of the production means, which will ensure the optimum part processing. This requires systematically processing of information characterized part population.

The analysis of structure of machined part spectrum considered from the point of view of functional system, enclose the following actions [14]:

1. – *Data collection* – it aims to determine which parts will be analyzed, and which data pertaining to these parts should be considered; the effect of these actions is a part database,
2. – *Data analysis* – its aim is usually the grouping of part in the spectrum; then it covers: determining of part similarity conditions, defining with which groups of similar parts we have to do, and which attribute characterize these groups
3. – *Solution of problem* – the end stage of the actions, which effect is to determine which manufacturing facilities should be used, which number of production means is necessary, which from alternative solutions is most effective economically.

If, due to the production kind and scale of which we have to do with a great part variety, then as a rule there would be unprofitable to install one flexible manufacturing system to produce all of these parts. Such a system would have been very complex and its use level and economic effectiveness would be then very low, but the investment costs high. The central problem by analyzing the structure of wide part spectrum is then to define groups enclosing the parts similar to itself according to accepted criterions, so as to undertake rational decisions about what range of production will realize the flexible system and what be its structure. Rightness of undertaken decision will be depending on the fact whether we shell possessing possibly full description of considered parts, including their entire features essential from the point of view of planning the system. Setting – up such part features, are depicted on Fig. 7.1.

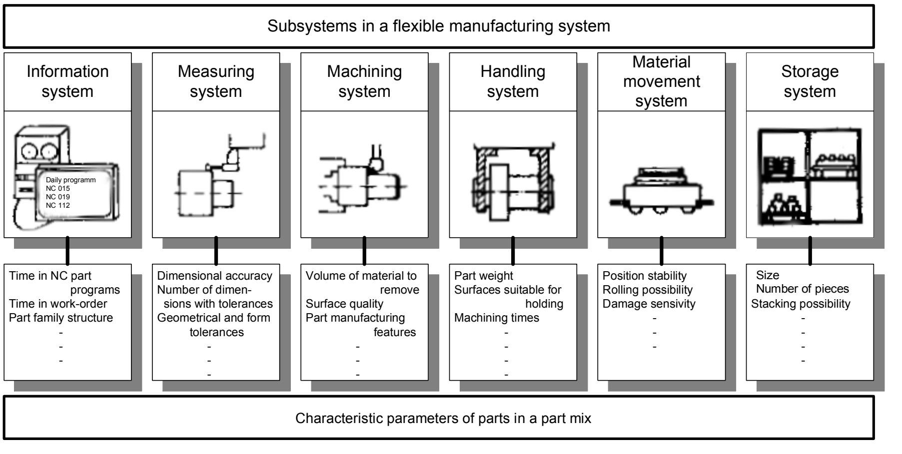



Fig. 7.1. Attributes of parts in a part mix

As a basis to systematize these features, has been accepted the structure of flexible manufacturing system, divided into appropriate functional sub-systems. Information taken into account by consideration the part features may be grouped in three levels:

- The level of product and assemblies; covers all information pertaining to products consisting of many elements (machined subjects),
- Level of the machined part; including all information, which will can be directly assigned to the defined part being machined, as e.g. material type, semi–product type, dimensions, machining time etc.,

- Level of elementary shapes, which includes information about particular shapes of elements out of which the machined part consists; here may be mentioned such a data as e.g. geometric shape, kind of surface, function, machining requirements.

All information included in the particular levels, may be divided appropriately to their kind, onto the following:

- Data referred to the part structure,
- Data referred to their functions,
- Data describing the part shapes,
- Technological data,
- Data concerning the work order.

### 7.1.1. STRUCTURAL ANALYSIS

Defining, assessment and processing of data referred to certain part spectrum is called "structural analysis". Similarity of parts belonging to such a spectrum means, that certain properties and/or association of these properties appear repeatedly with similar intensity. The structural analysis in general gives the answer to such question as:

- Which groups appear in considered part spectrum,
- Which parts belong to these groups,
- What distinguish particular groups of each other,
- How the part attributes are distributed in particular groups,
- Which connections between the part attributes are present in particular groups, etc.

The analysis of a wide machined part spectrum is a complex problem. One of actually used auxiliary means to finding the solution is the *cluster analysis*. With the help of this method are created the define groups of parts in their certain set. The „cluster analysis" allows making an optimal division of this set into classes, or partitions, and so:

- All parts in a given class present the best similarity,
- Parts belonging to various classes show the highest dissimilarity to each other.

The algorithm of cluster analysis is schematically shown on Fig.7.2.

Such an analysis is helpful in the stage of system planning, when the problem is to define the optimal configuration of the system and proper selection of its components (manufacturing equipment, stores, transport and manipulations means), as well as during its use, with the reference to:

- Selection of means to arrange the system (e.g. tools, fixtures, gripping devices) optimally adapted to suit the needs, and
- Optimization of the sequence of parts machining.

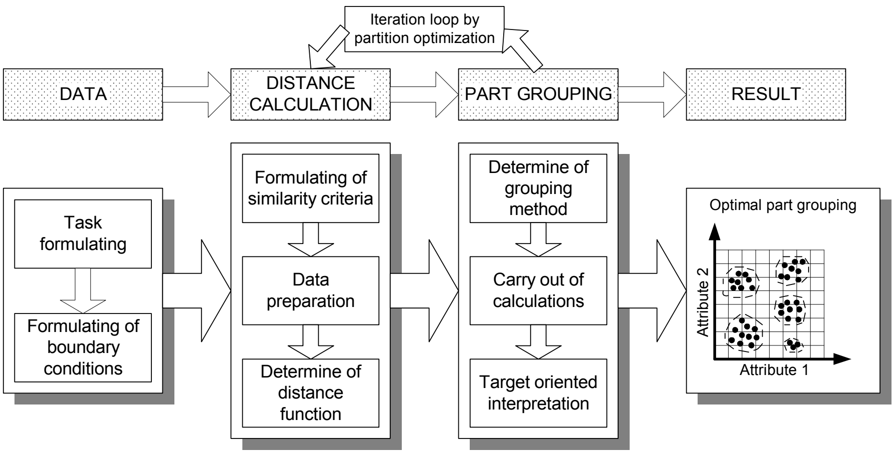
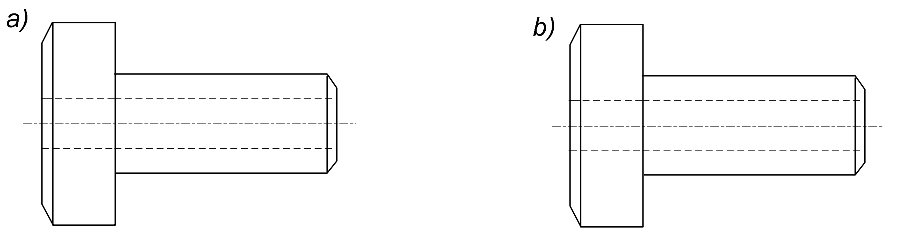



Fig. 7.2. Algorithm of cluster analysis of a part mix

## 7.1.2. GROUP TECHNOLOGY

The possibilities to split a part spectrum into groups of similar parts, according to accepted similarity criterion are also useful in *group technology – GT*. Group Technology is a concept of manufacturing closely associated with flexible automation. The concept of group machining appeared in the manufacturing technology at the end of 1950s (Sokołowski, Mitrofanow) [32], but became significant and spread after appearing the flexible manufacturing automation. GT is not simply the formation of machinery into manufacturing cells, although cellular arrangement is a logical consequence of group technology application [29]. The term *group technology* is a generally defined concept of production organization depending on grouping the produced parts into "families" with the aim to draw from their similarities advantages in the process of manufacturing, with respect to the shape, dimensions, material, and technological process of manufacturing or assembly. In the process of machining, the most important is the technological similarity of parts, although the other criteria of grouping should not be omitted. Parts that differ significantly by shape may be technologically similar. On Fig. 7.3.

are shown examples of parts of identical shapes, but technologically different, whether Fig. 7.4 presents parts varied very much with respect to shapes and destination, but of similar manufacturing processes.




| a) | b) |
|---|---|
| *Dimension tolerance: +0,15 mm* | *Dimension tolerance: +0,001 mm* |
| *Annual production volume: 200 000 pcs* | *Annual production volume: 200 pcs* |
| *Material: St5* | *Material: H18N10MT* |

Fig. 7.3. Two parts with identical shape but fundamental different processing

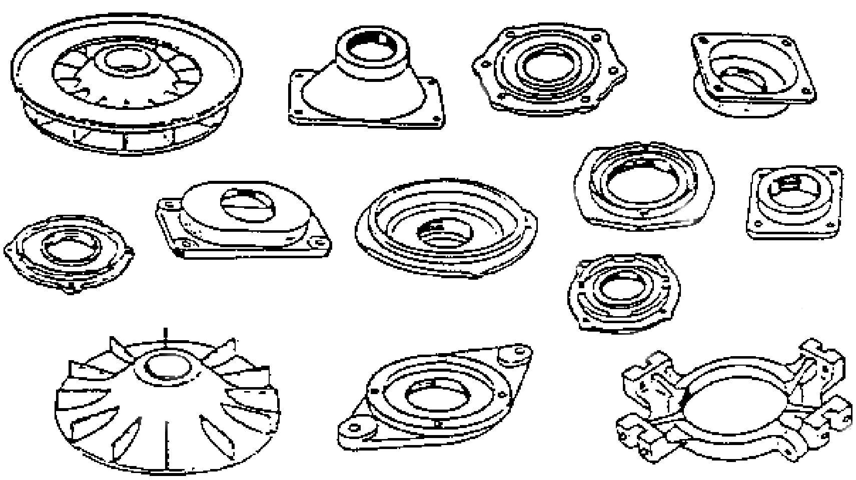


Fig. 7.4. Parts with significant different shapes and destination but similar processing

The application of GT brings with itself different practical advantages in all enterprise divisions and not only in production directly.

For parts to be grouped based on either design characteristics and features or manufacturing processes, they must be classified into predetermined categories and coded for retrieval and use. Classification and coding are computerized tools used to capture the design and manufacturing features of parts; they provide the ability to retrieve and analyze data by desired feature.

Parts classification and coding system has come to be known as the glue of group technology, and as means to identify the various design attributes or manufacturing features for part grouping.

The primary objective of a classification and coding system is to develop a multidigit code number for each part that identifies its major attributes and features essential to its placement in a particular part family. The first such a system has been proposed by H.Opitz [35]. Fig. 7.5 shows the principle of part coding in this proposition. The part in this system is described by a nine digit number.

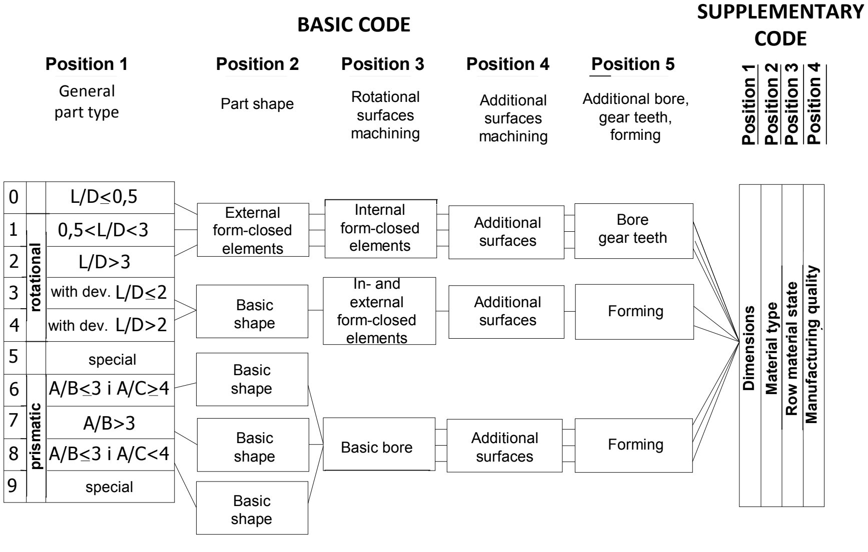



Fig. 7.5. Generic example of a design feature classification and coding scheme according to H.Opitz

Besides, of the shown coding system, there are known about hundred another systems, out of which many are based on the Optitz's proposition. Actually, there are most commonly used two systems: the DCLASS - used to describe rotating parts, and MICLASS - enabling also the description of prismatic parts.

Commercially available and user-specific classification and coding systems have coded part designation ranging from eight to thirty-five alphanumeric characters in length. In general, each digit has a value of zero to nine, with the first digit identifying the general part type and each succeeding digit identifying the next subgrouping. Part coding is actually made manually and is time consuming. There are therefore under preparation method of automatic generation of codes based on design in the CAD techniques.

## 7.2. WORKPIECE FLOW IN FMS

The flow of processed parts is the main material stream in a flexible manufacturing system. The whole of associated with it problems includes the sub-system called as *workpiece system*. The main goal of the workpiece system in this case is to assure that:

*After finish of machining of a part, on the machine tool will turn the, identified by machine controller and suitably fixed, next part up.*

Fulfillment of this task requires realization of following functions:

1. Storage of the parts,
2. Part transportation,
3. Part changing on the work station,
4. Part positioning and fixing on the machine tool
5. Identification of part and its condition.

The solutions applied by realization of these functions are depending on the class and size (mass) of machined parts and on the type of machine tool.

### 7.2.1. AUTOMATED PART STORAGE AND MOVEMENT SYSTEM

Material and components, parts, tools and fixtures are stored in:

- Central stores (mainly for material and finished parts),
- Internal part queuing (buffers), and
- Integrated on workstation stores (tool magazines, tool matrices, queuing carousels for parts).

The problems of central stores and material transport are within range of the entire manufacturing system logistics and are discussed separately. In this chapter, are mentioned only the problems of buffers and integrated stores. They are integrally connected with the workstations and as a rule are not central managed.

## 7.2.1.1. INTEGRATED PART STORES

They are featured by design variety associated first with the part types and consequently with types of machine tools with which they appear. Therefore, the boxy parts are fixed, as a rule on pallets and hence the flexible manufacturing cells with machining centers are equipped mainly in pallets stores. They may be of various designs depending on the number of pallets. By up to 8 pallets, the store may have the form of a rotational table (Fig. 7.6).

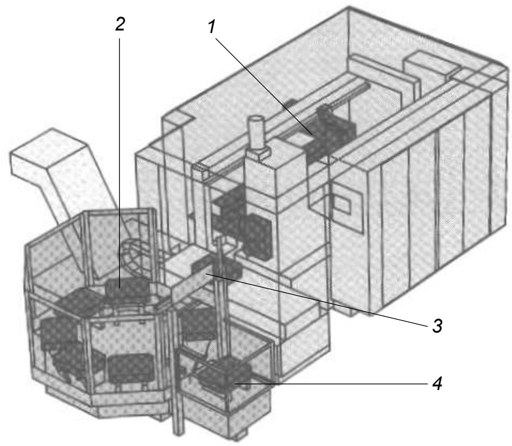



Fig. 7.6.
Eight-pallets store in form of a rotary index table:
1 – machining centre, 2 – pallet store, 3 – pallet changer, 4 – pallet loading

With a higher number of pallets (up to 16), it may have a linear structure (Fig.7.7), or rack-type store (by ~50 pallets and more).

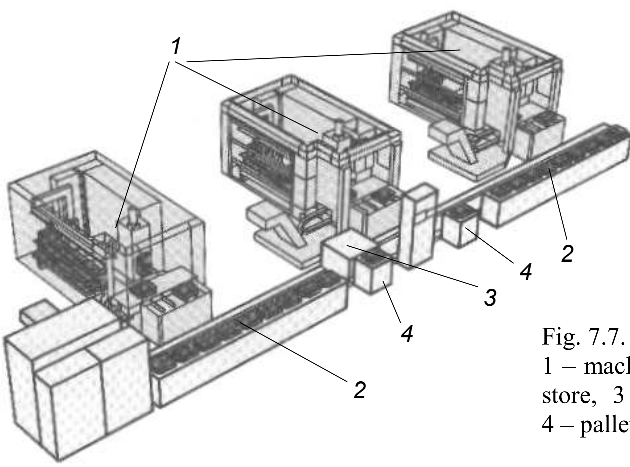



Fig. 7.7. Linear pallet store:
1 – machining centers, 2 – pallet store, 3 – pallet transport car, 4 – pallet loading

Generally, the pallet storages are divided onto active and passive once. The criterion of division in this case is the part mobility. In passive stores, the parts do not change its position, but are taken from the store by a special changer, manipulator, or robot. In the active stores however, they are moved in order to bring them to a position in which the changing takes place. Thanks to coding the pallets, there can be in the store various machined parts if MCU has in its memory the program of machining (or, also, it can receive it from a DNC computer).
For fixing the rotating parts, machined on lathes and grinding machines, there is no need to use intermediate elements similarly to pallets. To transport them and storage there are but used transport pallets, which are suitable to set them in stockpiles. Such a stockpile is the simplest solution for an internal part queuing. A manipulator or an industrial robot (Fig.7.8) operates the storage in question.

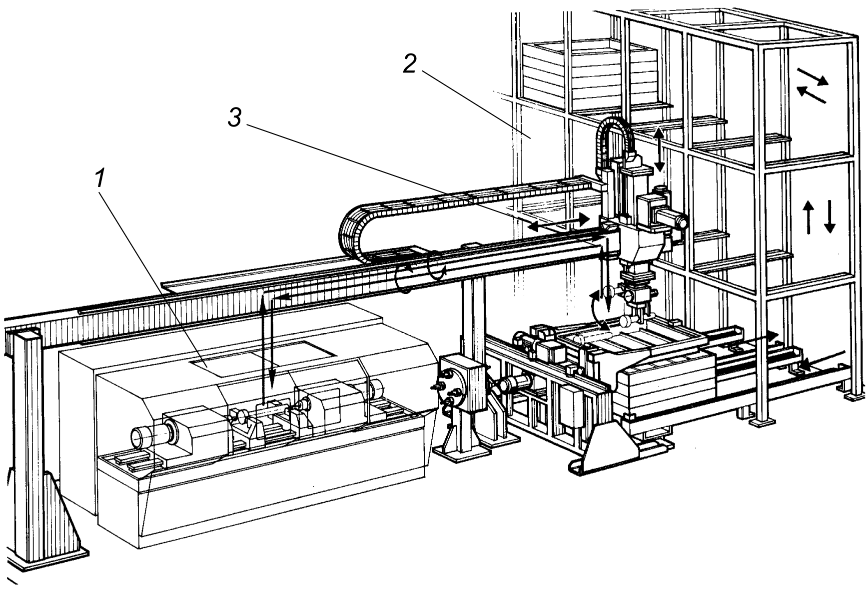



Fig. 7.8. Flexible manufacturing cell with turning centre and stockpile storage operated by the gantry robot: *1* – turning center, *2* – rack store, *3* – robot

Another solution are special stores integrated with machine tool equipped with automatic part changer (analogical to tool changer in machining centers) [13]. The stores are designed suitable to the form of machined parts.

## 7.2.1.2. BUFFERS

The buffers are meaningful first of all in manufacturing lines, including the flexible ones. In manufacturing, we have to do, in general, with three kinds of connections between workstations (Fig.7.9): loose, flexible and rigid, whereas in flexible automated manufacturing, there appear only the second of them.

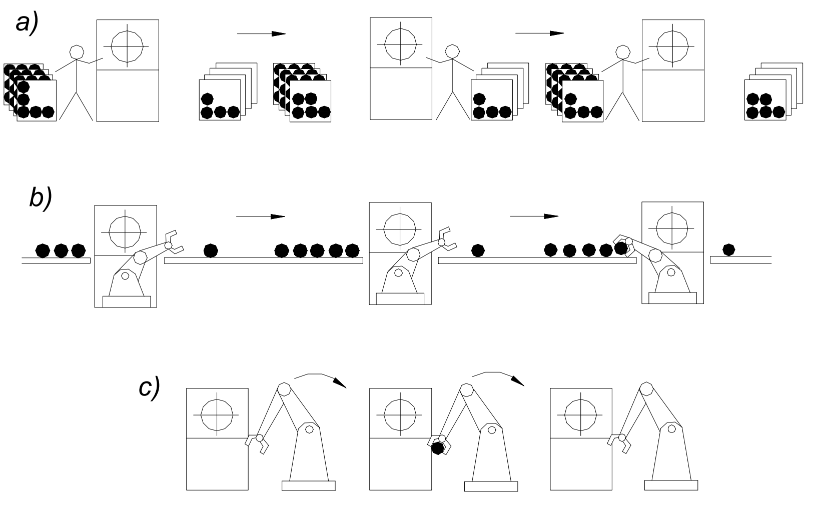



Fig. 7.9. Types of connections between processing stations:
a) loose, b) flexible, c) rigid

In the flexible connection, there are four types of buffers (Fig.7.10) flow through, flow with reversible buffer, circulating and with direct access.

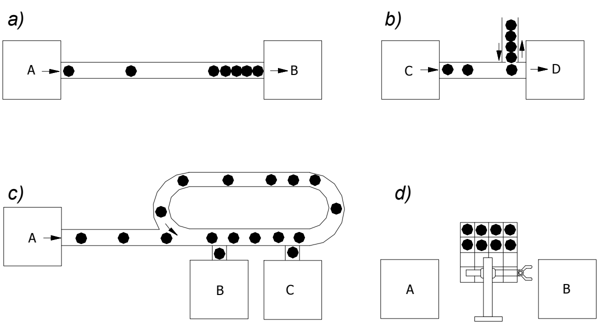



Fig. 7.10. Types of buffers in flexible connection of processing stations: *a)* flow through, *b)* flow with reversible buffer, *c)* circulating, *d)* with direct access

When planning manufacturing system built-up of a chain of workstations connected between themselves by a transport system, an important role plays a selections of suitable number of buffers of appropriate capacity, and their proper placing. The aim of buffers is to ensure the continuous function of the system and to avoid unforeseen work stoppage.

Such breakdowns may be caused by:

- Failures of system components: they may be of various character and causes,
- Disturbances in part flow associated failure of with structural connection of workstations in the system; e.g. standstill of one machine tool because the already finished workpiece cannot be transported to the next station.

The improvement of utilization rate of the entire system may be achieved by the following measures:

- Disturbances prevention,
- Disturbances elimination,
- Disturbances compensation.

The effective prevention of disturbances is very expensive and rapid elimination them is the problem of monitoring and diagnostic system. However, the use of buffers enables effective compensation of the structural part flow disturbances.

In the course of planning the system, there should be carried out the buffer optimization. To this end, there were elaborated special optimization programs [37]. They are based on determining of “bottle necks” location in the system and maximum of buffers capacity by defined in percentage system utilization rate. The criterion of optimization is the cost minimization. Fig.7.11 presents an example of optimized buffers locations and their maximum capacity in the transfer line to crankshafts machining.

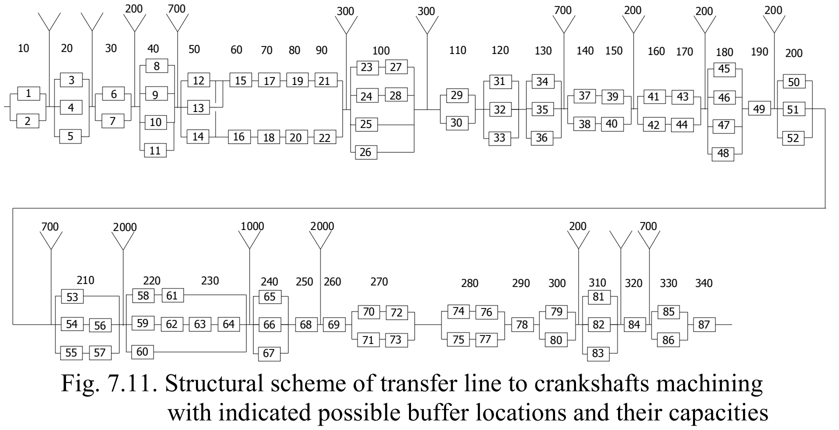



Fig. 7.11. Structural scheme of transfer line to crankshafts machining with indicated possible buffer locations and their capacities

In the first part of the line there are mainly made the turning operations, and in the second - mainly grinding. The line consists of 87 workstations realizing 34 operations (marked on the scheme by numbers from 10 to 340). To make some of them, there are foreseen several stands, to increase the line productivity. In the first step of optimization are grouped all in parallel working stands. In the second step, the next grouping has been made connecting the less loaded stands, or such ones between which due to technical reasons was no place to locate the buffers. In this way there were obtained 17 possible buffers locations. In turn, there were obtained the required capacity of buffers, with the assumption of using the system in 93%.

### 7.2.2. PART FIXING AND CHANGING

The method of part fixing on the machine tool depends mainly on its size and shape. The used solutions in design are the results of tendency to ensure the following:

- The ease of part changing,
- Accuracy and repeatability of its position in the machine tool workspace,
- Short time of part changing.

In case of prismatic parts small and medium size, particularly often appearing in the use of FMS, their quick changing, and precise fixing is ensured by the use of intermediate elements in the form of pallets (Fig.7.12). Well-designed pallets may enable to fix at a time several parts, what allows the reduction of part changing time.

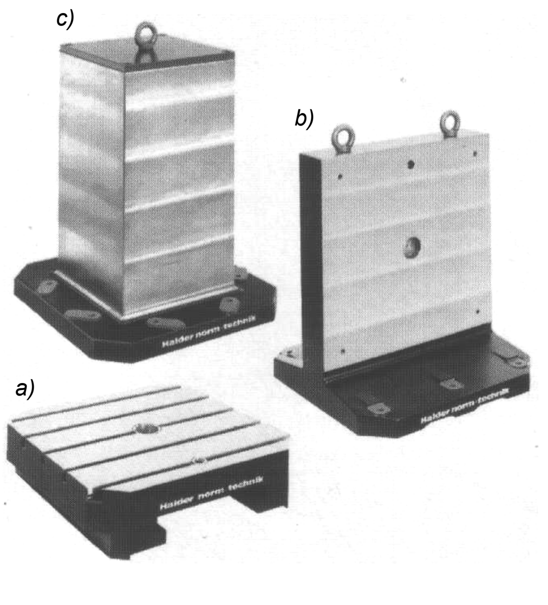
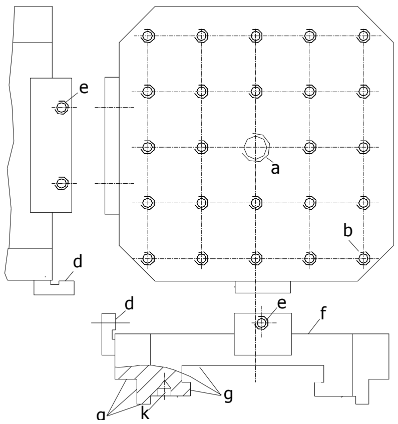



Fig. 7.12.
Various types of pallets used in FMS: a) plate, b) two-sided tombstone, c) four-sided tombstone

The most often used, are plate pallets with T-slots, or threaded holes. They are already in many countries standardized [26]. Fig.7.13. presents en example of standard (Japanese standard JIS B6337-1980) of plate pallets with threaded holes, produced in various sizes [22].




| Nominal size mm | Capacity (fixed part) kN | Weight kg |
|---|---|---|
| 400 | 250 | 80 |
| 500 | 400 | 140 |
| 630 | 630 | 280 |
| 800 | 1000 | 540 |

Fig. 7.13. Example of a standard pallet: a - central bore, b - tapped holes for mounting of parts or fixtures, d - side basis plane, e – tapped hole for pallet pulling, f – surface to part mounting, g – guidance surfaces, k – pallet positioning hole

Trends towards shortening the part changing time, to increasing the accuracy of its positioning in machine tool or coordinate measuring machine workspace, and to increasing of the system flexibility degree, carried to the appearance in industry of the pallet systems [15],[68],[71], and comprehensive solution of systems for part fixing [63],[72]. Besides, of pallets they include pallet changers, work holders, hydraulic systems with feeders to fix the pallets and fixtures, and integrated fixing control systems. Fig. 7.14 shows the part or pallet fixing system *vb Dock Lock* of VISCHER & BOLLI. This system can be use both by the manual operating of the machine tool, as well as by the automatic part changing.

Pallets are making easier: transport, changing, and fixing of the part on the machine tool. To assure part accuracy pallets must be equipped with suitable fixture. Fixtures must hold workpieces accurately and rigidly while providing, in some cases, multisided part access for all cutting tools, including their approach and departure paths.

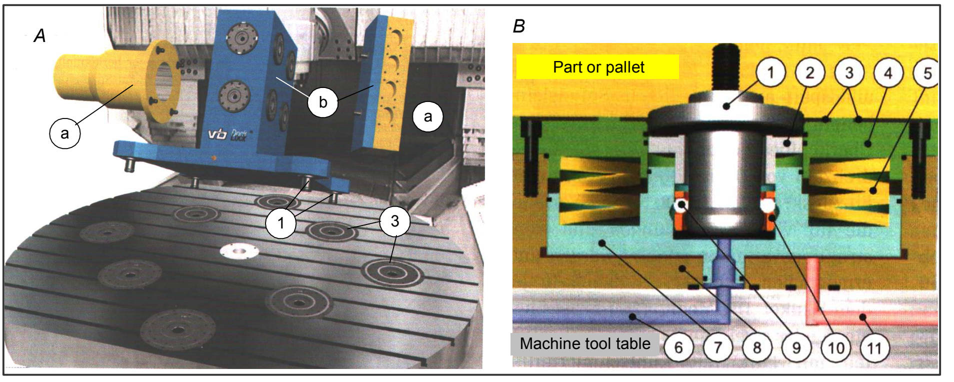



Fig. 7.14. System of part and pallet fixing on the machine tool table:
*A* – machine table with the *vb Dock Lock* fixing system, *B* – system functioning principle, *a* – part, *b* – pallet, *1* – multi function pin, *2* – pin's guide , *3* – stick rings, *4* – cylinder cover, *5* - set of disk springs, *6* – compressed air (pin blowing out), *7* – piston of clamp loosening system, *8* – cylinder body, *9* – balls, *10* – cage, *11* – pressurized oil (for clamp loosening)

Fixture design should be simple, and standard components should be used whenever possible. In flexible manufacturing systems, there are usually used modular fixtures (Fig.7.15).

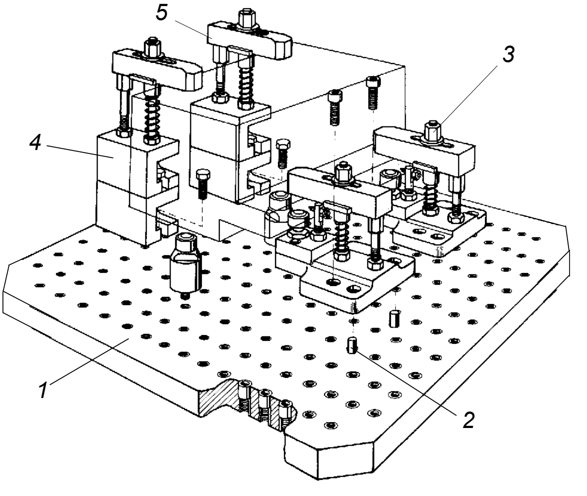



Fig. 7.15
Modular fixture: *1* – base plate, *2* – locking pin, *3* – clamping element, *4* – distance piece, *5* – clamp

Modular fixturing employs the use of reusable, interchangeable components that can be assembled and torn down based on changing part requirements. The objectives behind modular fixturing are the same as those for table setups or dedicated fixtures; the part must be positioned, located, and held securely in place.

Modular fixtures rely on a base plate or sub plate or a tombstone-type base. Both base plates and tombstone-type base can be mounted directly to the machine table in a stand-alone NC machine environment or to a pallet in a cellular or FMS environment. Fixtures components are stored in bins and assembled as needed. Components selection and fixtures configuration can be automated (e.g. program FixPlan being a module of integrated system of manufacturing process planning IMPACT [50], or a system of fixtures planning VPS of Halder [65]). The designing of machining fixtures is based in this case on information about the machined part, and on information about machining process and the machine tool.
Use of pallets and modular fixtures requires special station in FMS to fixtures building and part loading/unloading.

To be autonomous, the manufacturing system, in the area of part flow, must be provided with automation of part changing. Part changing may be made in various ways. In case of machining centers, the functions of loading and unloading (part exchanging) is usually made manually during machining, whereas the changing itself is carried automatically with the use of pallet changers of various solutions. Changing the pallet according to these solutions may be made through shifting it (Fig.7.16) or by changer rotation (Fig. 7.17). The changer drive may be hydraulic, or mechanic.

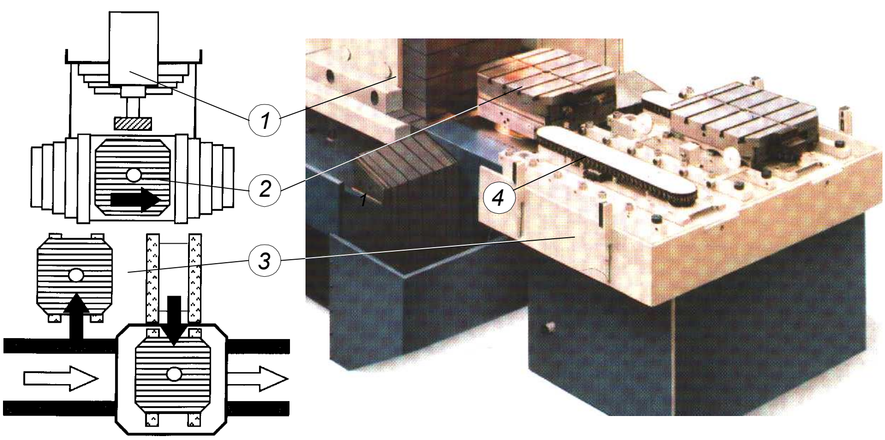



Fig. 7.16. Shifting pallet changer: *1* – machining center, *2* – machine table with pallet, *3* – pallet changer, *4* – pallet shift chain mechanism

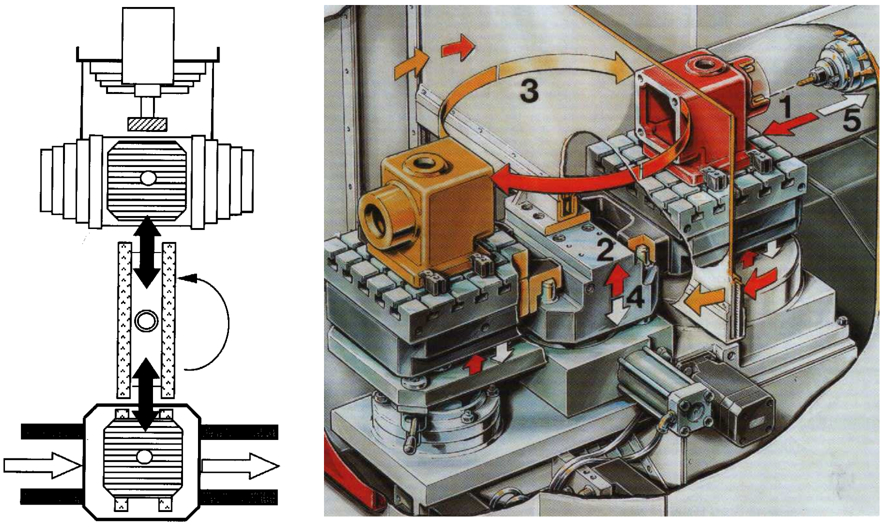



Fig. 7.17. Rotary motion pallet changer – arrows indicate motions by the pallet changing and numbers indicate sequence of motions

The rotational part fixing in automated systems does not differ in principle from fixing with which we have to do in conventional machining. The intermediate elements (such as pallets by prismatic parts) there are not used. The solution of problems associated with automation of these functions moves then to the systems of storage, manipulation and transport. Small parts are stored and transported with the use of so-called storage-transport pallets. Such pallets must be suitably adapted to the part shape and size. To rationalize them there was elaborated a modular pallet (Fig.7.18) enabling building of standardized module a pallet to fulfill the requirements of defined part spectrum.

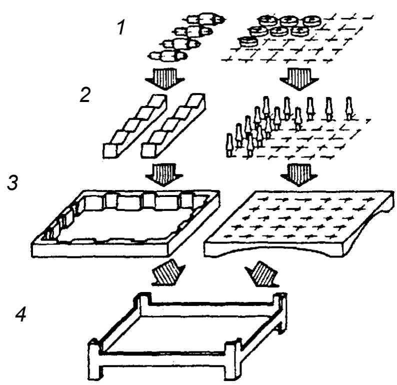



Fig. 7.18

Modular transport-storage pallet for rotational parts:
*1* – workpieces, *2* – workpiece shape oriented pallet component, *3* – general part type oriented pallet component, *4* – pallet frame

Automated rotational part changing (both on lathes as on grinders), may be realized with the use of:

- Industrial robots,
- Gantry robots,
- Loading/unloading device integrated with the machine tool,
- Autonomous loading/unloading device.

The industrial robots were used, first of all, in the flexible manufacturing islands. However, the use of them were often not economically justified because their wide application possibilities were not realized. More often there are used the gantry robots. Especially convenient is the use of gantry robots in case of lathes (Fig.7.19), and for operating of several centers, machining small parts stored on pallets in the stockpile storage at the turning centre (Fig.7.20). The advantage of gantry robots is also the easy access to machine tools.

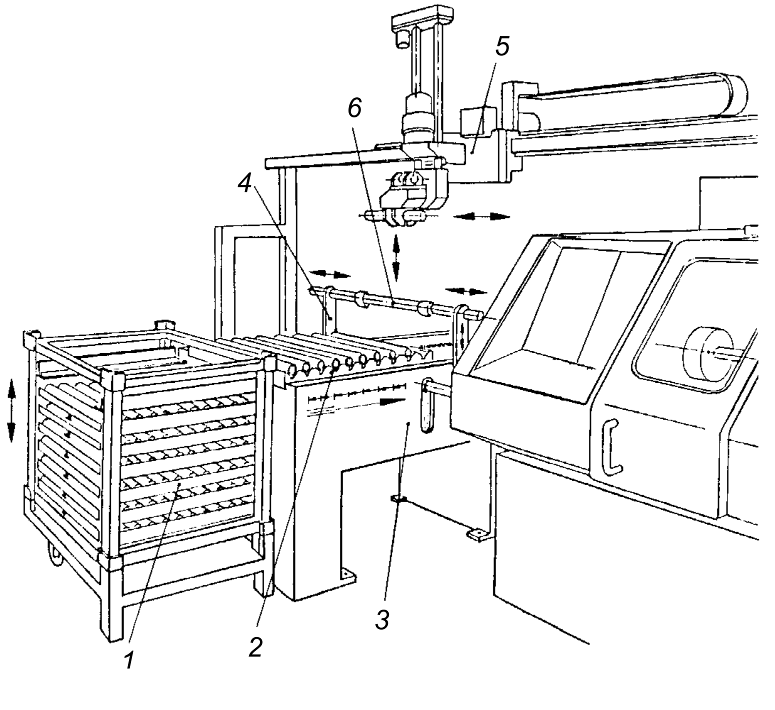



Fig. 7.19. Gantry robot with at-the-machine pallet-store and loading installation:
*1* – pallet store, *2* – transport pallet, *3* – table with a stroke device,
*4* – lifting, *5* – gantry robot, *6* – part raising device,

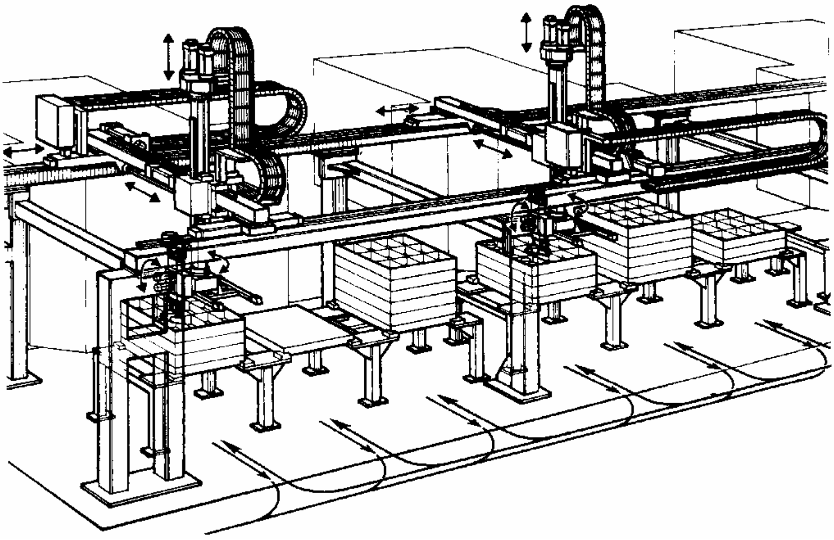


Fig. 7.20. System of gantry robots realizing loading/unloading functions for several turning centers

In the autonomous loading/unloading device are included: storage, part changer, and storage and changer drive [13]. The device structure should ensure:

- Flexible storage and changing of possibly wide part spectrum,
- Short time of the store set-up change,
- Universal gripping device enabling part changing by a wide part spectrum, without the store set-up,
- Possibility to install the device by possibly many various NC lathes.

The stores of autonomous loading/unloading devices may be of wide various designs depending on the part spectrum. In case of not a great size not exceeding the mass of 10 kg, there are foreseen to apply the horizontal stores (Fig.7.21).

Parts of greater size have stores of vertical structures. Part changing is realized either with the use of special, single or double arm changer (Fig.7.22), or with the help of manipulator equipped with a gripper suitable to the part shape. In case of a changer, the arm length is depending on the distance from the spindle to the store, taking in consideration a given machine tool.

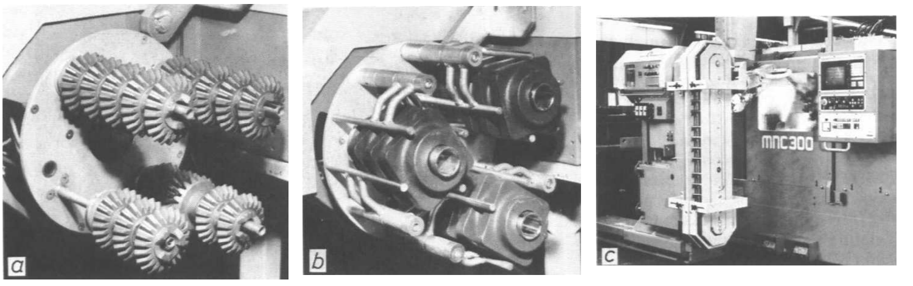



Fig. 7.21. Rotational parts stores: *a), b*) – stores for parts clamped using chucks,
c) – store for shaft type parts

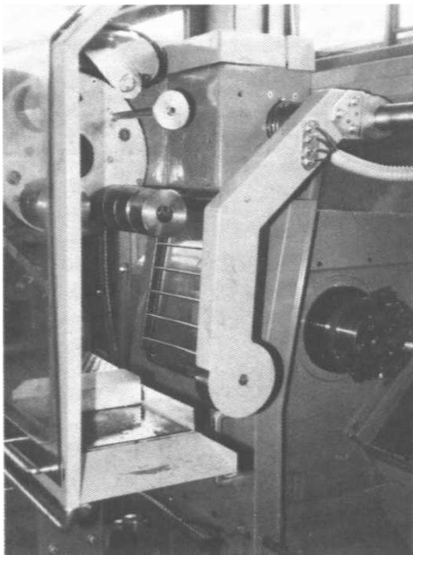


Fig. 7.22. Single-arm part changer

## 7.2.3. IDENTIFICATION OF MACHINED PARTS

The unmanned machining of defined part spectrum is possible only when identification of part and its condition is ensured. Method of identification depends upon the part transport solution and control thereof. In case of closed-loop FMS system when parts are moved around a conveyor loop from machine to machine, each pallet is provided with a microchip identification system with the help of which it receives information to which machine tools is the workpiece directed. Fig. 7.23 show places, on the pallet where the microchips are present.

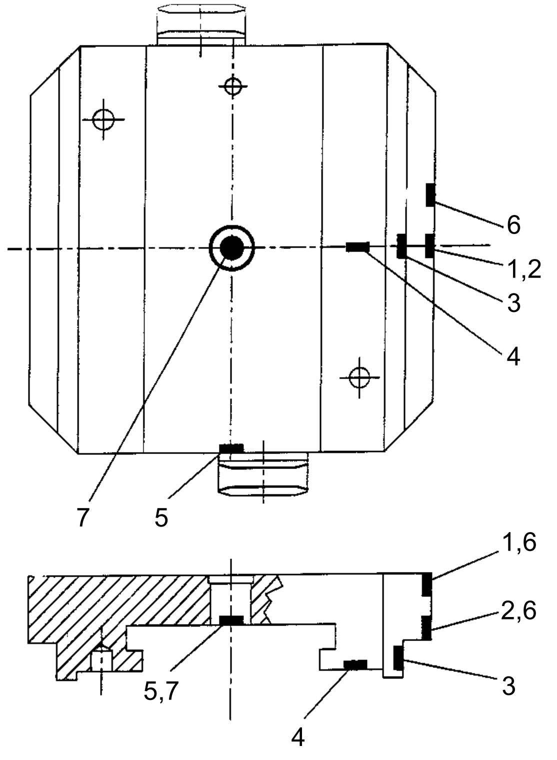



Fig. 7.23.
Possible placing of microchips on the pallet – numbers indicate the possible places

At each workstation, the information is red and when the circulating part comes across "its" machine tool, the machining begins. If there is the necessity to realize further operations, or measurements, the code is being changed in the way that it directs the workpiece to appropriate workstation. After the machining, the code is being changed and part is retired from circulation and returns to the loading/unloading station. Should on the same machine tool be machined various parts, the information contained in the code are activating in MCU part machining program, belonging to given workpiece. If such a program does not exist, pallet is after certain time withdrawn from the machine tool.

If transport is realized by larry cars, or AGV, coding is not applied, and managing of machined parts are taken over by computer which controls the transport system. After loading the pallet, operator feeds into computer the number of pallet, number of part and number of workstation (machine tool). From this moment on, the computer takes over control of workpiece flow. The following are the tasks to be carried out:

- Check the state of machine tools, to find which machine tool has a free input,
- Send a command initiating transport of pallet with appropriate part from the pallet storage to this machine tool,
- Transport this pallet to the machine tool and exchange it i.e. leave it for machining and take away the pallet with the ready part,
- Check, whether the wash-station is free
- Move the pallet to wash-station and leave it, take away the pallet with a washed part,
- Move the machined and washed part to the loading/unloading station and give it up.

Additional task is to state the priority, when several machine tools present being free to operate. There is a principle that one should take care to fully load the most expensive machine tools.

If a series of identical parts is machined, or the operator does not optionally change the sequence of pallets with various parts, then the above-mentioned data are applied only a single time to the first part of the series.

# 8. FMS LOGISTIC SYSTEM

The FMS logistic system includes installations realizing the functions of storage, transport, handling, and control of these functions. The *storage* brings to mind break in the material flow, *transport* - changing the location that means material displacement, and *handling* -displacement with additionally orientation changing. Separating the functional areas may have a real or conventional character, depending on realization of the functions - separately, or jointly.

## 8.1. STORAGE SYSTEMS

The storage system has the following tasks:

*To create a parts, tools, and fixtures (or their components) inventory being necessary for unmanned working of FMS for a long time.*

To fulfill this task, it requires the existence of store structure having necessary number of storage places, and realizing the following functions:

- Identification of stored object,
- Receiving them, storing it in a computer-assigned location, and retrieving them when necessary,
- Control and management of store functioning.

The general structure of factory's storage system is shown on Fig.8.1.

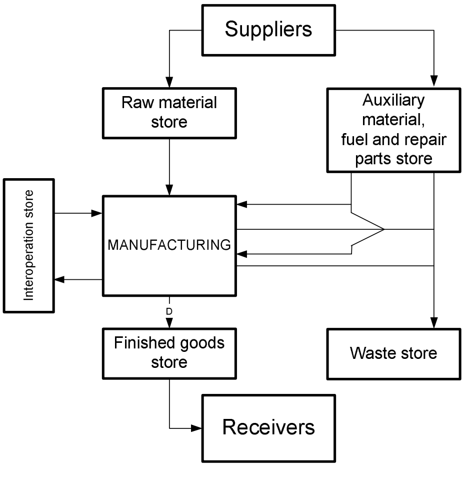



Fig. 8.1. General structure of factory's storage system (according to [10])

Depending on the factory size, production type, automation level and accepted organizational solutions, the particular kinds of stores, may act separately, or may be grouped in multi-task central stores. Each of the stores, which may act in the factory, presents a complex system realizing the above mentions functions.
They are two types of storage systems:

- Static, and
- Dynamic.

In the static systems, the stored objects do not change their locations from the moments of their loading to the moment of leaving the store, whether the operations of loading/unloading are made at the same place.

In the dynamic systems, the stored objects are displaced after loading. Loading and unloading may be followed in different places.

Depending on the role in the company and in the manufacturing system, the stores may be divided onto:

- *Central stores* providing services to production department, or for the whole plant,
- *Buffers* used by several workstations, or by a cell,
- With workstation *integrated stores*.

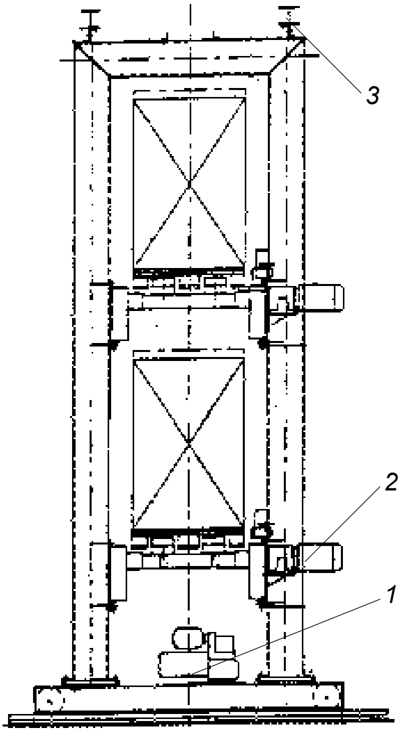
Depending on the production plant size, organization of production, and the range of area occupied by the installed, flexible manufacturing system, there may be applied various types of stores, both, centralized, or “dispersed”. Therefore, out of among realized flexible manufacturing systems, -15% are equipped with only central store, -45% with only buffers and integrated stores, and -40% has both, the central and “dispersed” stores. From the organizational point of view of workpiece flow in FMS, all these stores fulfill the role of buffers containing inventory necessary for unmanned production.

To the central store, there have a free access all workstations. The buffers are often the component part of transport system. These stores are used to balance the fluctuation in feeding associated with transport and machining. Their task is to ensure appropriate use of machine tools.

The central stores are most often high stacking rack stores serviced by special stacker cranes, Fig. 8.2.

Figure 8.3 shows the high-stacking central rack store, with a staging area shared by the two systems: flexible manufacturing system and flexible assembly system, in electric motors production plant.

Fig. 8.2.
Example of a stacker crane construction:
*1* – crane movement motor drive,
2 – vertical movement of platform drive,
*3* – crane movement stabilizing guidance



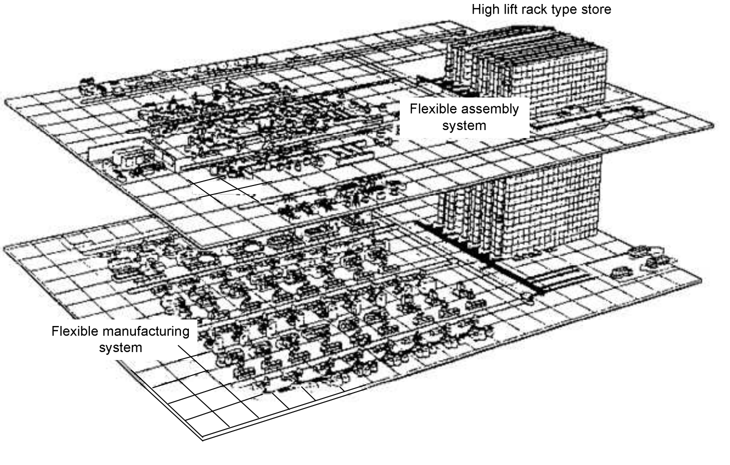




Fig. 8.3. Central high lift rack type store

These systems are located on two stories. Thanks to this, that the storage is developed vertically, there has been avoided the need of transport of plants from the machining to the assembly system. Such organization of storage systems markedly simplifies the transport system and the management of these both systems. This is particularly significant due to this fact, that in the plant in which this store has been installed, 40 various types of electric motors were produced, and the number of various machined parts were reached up to 900, at a batch number from 20 to 1000 pieces.

Another solution of storage system has been applied in plant producing the industrial robots (Fig. 8.4)

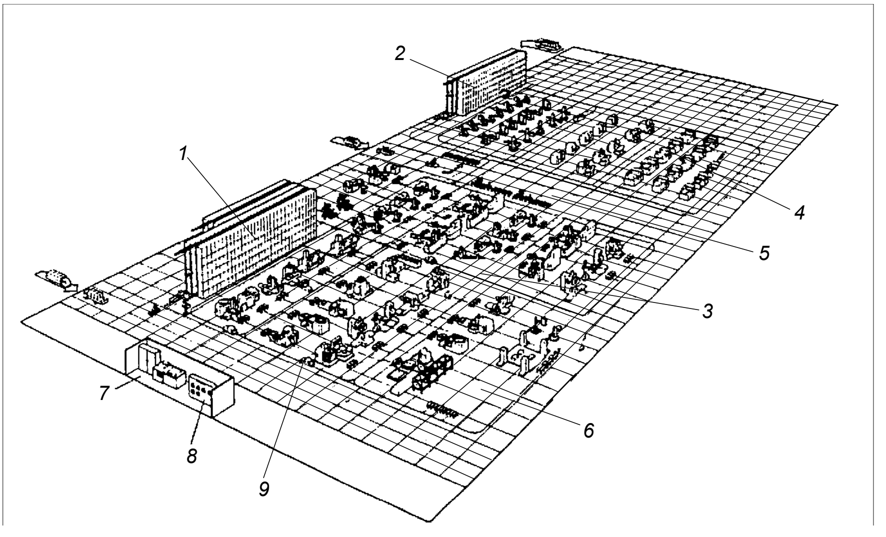



Fig. 8.4. FMS central storage system: *1* - automated high lift rack store for raw material and blanks, *2* - automated part and devices store, *3* - flexible manufacturing system (machining), *4* - flexible assembly system, *5* - production control, *6* - welding, *7* - central FMS control system, *8* - central monitoring system, *9* - AGV

The central store has been divided into two units: materials and semi-product store, servicing the flexible manufacturing system, and finished parts and subassemblies store intended to service the assembling department. The plant is distinguished by a variety of products (13 types of robots), at relatively small number in a batch. In the flexible manufacturing system, these are made 450 various parts in batches of 5 to 20 pieces.

In case of a system for production of relatively small parts, *mobile stores* may be used. On the Fig. 8.6 there is shown such a solution of storage system used in electric tools production plant [53].

There has been installed a flexible manufacturing system for the production of the whole range of motor shafts for these tools. The storage system has been in this case integrated with the transport system realized as a suspended rail system. The whole of the system covers two transport-storage systems: central store and inter-station store. The machined subjects are placed in containers suspended in transport system, whereas the central store and the inter-station store constitute independent systems placed on various transport levels. These levels are connected by a lifting station enabling the exchange of containers with subjects between the stores: the central one and the inter-station store. At each machine tool there is a lifting station, and an installation of loading/unloading, which enable to take out by the machine tool parts for machining, and handle to the store ready-made parts.

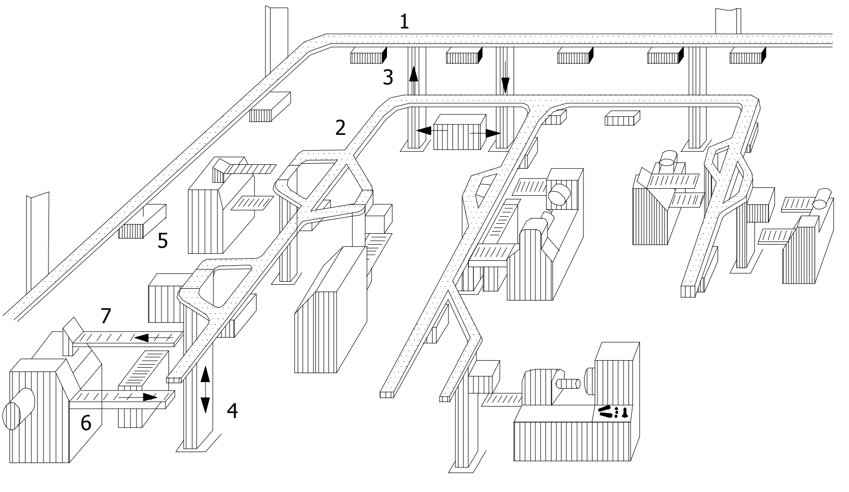



Fig. 8.5. Example of mobile storage system - suspended transport-storage system: 1 - second t-s system level - central store, 2 - first t-s system level – inter-station store and transport between workstations, 3 - both level connecting lift station, 4 - workstation lift, 5 - mobile store, 6 - machine tool, 7 - load/unload installation

The advantage of such a solution is place saving because of integration of storage and transport systems; the disadvantages that is the cost caused by the necessity to provide each working stand with a lifting installation as well as loading/unloading station, and connecting with the kind of transport significant rigid system structure.

The inter-station stores in the system of conveyor transport are simply buffers being a part of transport paths. However, in case of cars transport, these are integrated, automated stores of small or medium capacity consisting of the following components:

- Single, or double rack of 50 to 500 places,
- Automatic servicing installation being a small stacker crane,
- Autonomous control of microprocessor base.

Such stores are used for arrangement; computer managed storing of parts before and after multi-operational processing. Their control should ensure the possibility of connecting them to host computer, managing the manufacturing process (DNC computer). They may find application both in conventional, as well as in automated manufacturing.

## 8.2. TRANSPORT SYSTEM

The transport system is beside of information system, a component integrating all installations being included in FMS into one acting in coordinated way manufacturing system. The main goal of the *transportation system* in FMS is:

*To assure continuity of material flow in order to increase utilization of machines and other production equipment.*

To have the possibility to fulfill the task in automated manufacturing system, there is the necessity to realize the following functions:

- Material moving (workpieces, tools) along the given transportation path,
- Flexible connections with the storage system and processing stations,
- Identification of load and its condition and the processing stations,
- Connections with the handling devices.

The transport system, beside the control system integrates the particular constituent elements into one whole. When talking about the material flow, we have in mind first of all the parts and tools. Transport of chips however is as a rule, realized separately. For transporting parts and tools, may be used, depending on accepted solution of transport system, the same, or different transport means. Usually, these are various means especially therefore, that transport of tools is not in all

automated system. The classification of most often used transport means, is shown on Fig. 8.6.
Choice of means of transport for planned FMS depends on:

- System type (machining or assembly),
- Part spectrum (part type, size, weight),
- Assumed system configuration (on-line, closed loop, open field),
- Size of production (system size),
- Assumed system productivity,
- System automation level.

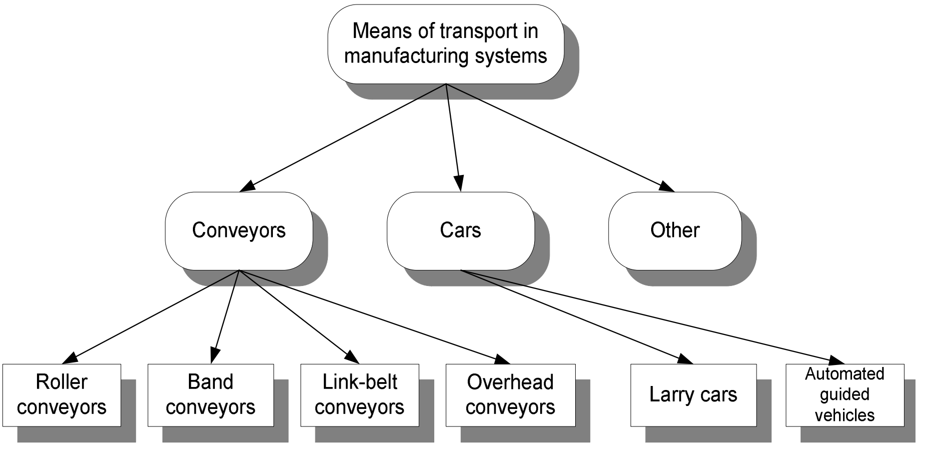



Fig. 8.6. Classification of means of transport used in FMS's

## 8.2.1. CONVEYOR TRANSPORT

Conveyors offer automated manufacturing users a variety of options from which to choose, depending on individual part characteristics and production requirements. They present a hardware-defined fixed path over which components travel to their destination. Conveyors are generally classified as either *overhead mounted* or *floor mounted*. *Overhead conveyors* may be either of the monorail power and free type or overhead chain type. Both power and free and chain-driven conveyors can handle medium to large part types such as automobile frames and bodies.

*Floor-mounted* conveyors are classified as *roller*, *chain*, or *belt* driven. This type of transport is first of all used in closed loop systems and, because of workpiece permanent circulation, is not suitable to computer control of part flow. Then, the workstations must be provided with the read-write heads and the transport pallets with read-write microchips. The conveyor is usually complex space structure, which restrict access to equipment for maintenance, support, and general cleaning.

1. *Roller conveyors*

In case of conveyors of this type, used in automated manufacturing systems, the transport path consists of steadily rotating, driven rollers. The movement is transferred on pallets through friction on the rollers. There are two ways of situating the rollers: perpendicular and parallel to the path. In the first case, they fulfill the role of roller race. Conveyors of this type are used in transport between workstations, between workshops, on assembly lines and in storage transport. In the assembly transport are also used conveyors of single rollers situated in axis of the path drive. (Gardo Trans). They are pressed with a steady force to pallets, which are moved on separate rolling guides. The inclination of rollers ensures the axis component of friction force enabling the displacement of a pallet.

2. *Chain conveyors*

The chain conveyors displace the load by means of a chain band, to which are fixed the load carrying members in the form of plates and troughs. The chain conveyor is working on the same basis as the belt conveyors.

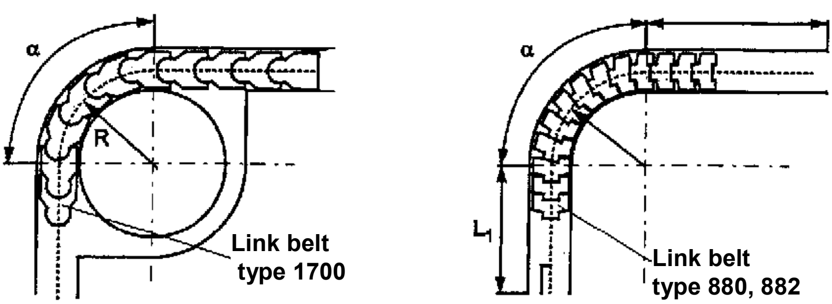



Fig. 8.7. Chain conveyor

The meshing plates form a chain of conveyor and are usually made of plastics. Thanks to their construction, this type of conveyors may operate on arcs (Fig. 8.7) and can work both in a straight movement as well as on circumferential path.

The trough conveyors with metal members find their application also in chip removing.

3. *Belt conveyors*

From among the tension conveyors, in the manufacturing systems, most often are used belt conveyors [17], and double belt systems of the firm Bosh [57]. This firm has elaborated a complex solution of conveyor transport in manufacturing systems, based on a concept of modular structure. The whole of the solution includes a series of types adapted to parts of different maximal masses (from 1.5 kg to 240 kg) and in this connection to pallets of different size (80mm × 80mm to 860mm × 1260mm) [57-62].

## 8.2.2. CAR TRANSPORT

1. *Larry cars*

The transport path is in this case strait lined, without curves and crossings. It is formed by exactly made system of two rails on which the car is moving, usually numerically controlled. The larry cars are usually utilized for transporting pallets, and are used in manufacturing systems for machining body parts. They are equipped with a pallet loading/unloading device (Fig. 8.8).

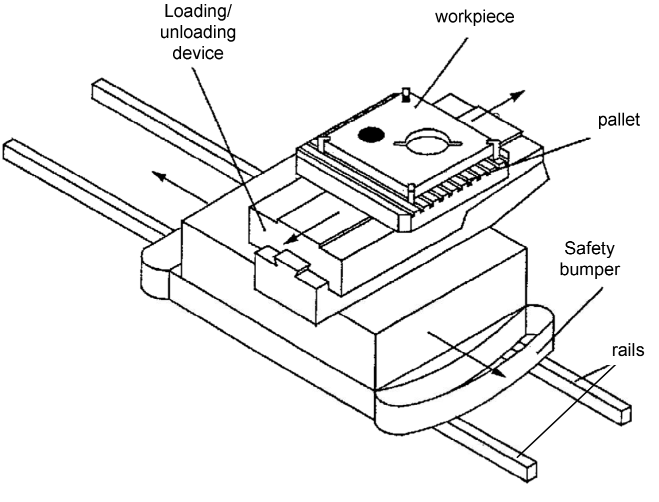



Fig. 8.8. Larry car

The advantages of rail transport are:

- High carrying capacity, reaching several metric tons, depending on workpiece size,
- Significant driving speed and transparent effectiveness,
- Exact and quick docking at workstation pallet changer,
- High reliability.

The cars are provided with measuring systems transmitting information to the transport system control computer about position and velocity. This enables running optimization that means accommodation of accelerations (positive and negative), to the inertia of carried load, what enables prevention of the damages in transportation. On each station, the car is before beginning the loading/unloading, exactly (mechanically) positioned and fixed. The pallet changing devices have usually the possibility of both sides operation what enables servicing the station at both sides of railway.

The disadvantage of this transport solution is a significant cost of construction and necessity to incur costs connected with rebuilding the railway by production changing. The larry cars are then useful first of all in the system with rigid structure.

2. *Automated Guided Vehicles*

Automated Guided Vehicles (AGVs), as we know them today, were developed in the United States in the mid 1950s and are defined by the Materials Handling Institute as battery-powered driverless vehicles that can be programmed for path selection and positioning and are equipped to follow a changeable or expandable guidepath. The computer, communicating via FM radio signals, gave AGVs the ability to travel on both closed and multiple loop paths and also handled traffic control and the queuing of multiple-vehicle systems. This onboard microprocessor and “land-based” AGV computer allowed for material tracking as well.

AGVs come in e variety of types and sizes and can be used in applications and environments wherever material is moved. AGV general types include:

- Towing,
- Pallet trucks,
- Unit load,
- Fork trucks,
- Assembly vehicles.

Most often, there are used two types of AGVs: hoisting and descending platforms, and fork trucks, front and side operating. The methods of AGVs guidance are classified according to physical path line realization (Fig. 8.9).

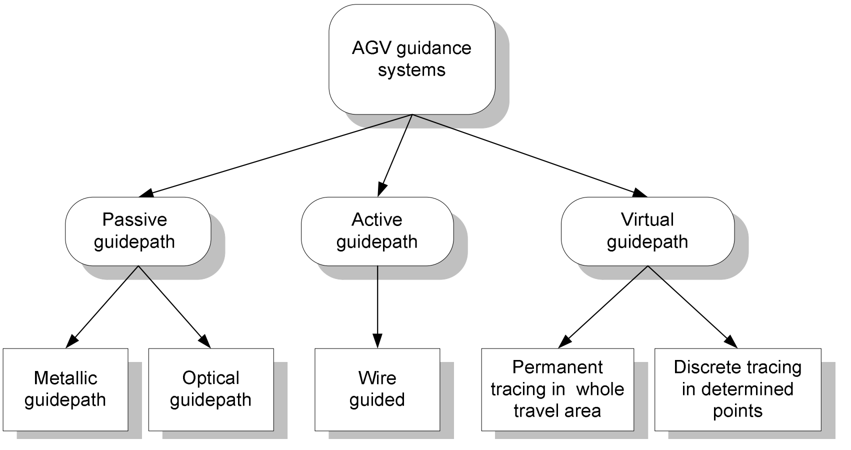



Fig. 8.9. AGV guidance systems

The guidepaths may be classified into passive, active and virtual. The *passive* is determined by lines formed on the floor surface through placing various materials, such as metal tapes, paints, or chemical substance. Following the line may be realized e.g. with the use of camera. The disadvantages of these solutions are in sensitivity on impurities and ease of damage of placed line, and dependability of the way the floor surface was made.

The majority of AGVs in use are battery-powered, wire-guided vehicles that follow energized wire embedded in the floor (*active guidepath*). Saw cuts are made in the floor about one-half-inch deep based on a predetermined guidepath route. Wire is laid in the saw cut and then epoxied over to form a smooth, unbroken surface for sweeping and maintenance (Fig. 8.10). In the wire flows alternating current of various frequencies (from 6 to 35 kHz) which generates concentric magnetic field along the running paths. In the cart, there are two coils: analyzing and reference coil. Their signals are continuously compared. The first of coils analyzes the magnetic field and if the cart goes away (turns) from guidepath, measurement of the phase between signals delivers impulse to the control motor, which corrects the movement direction.

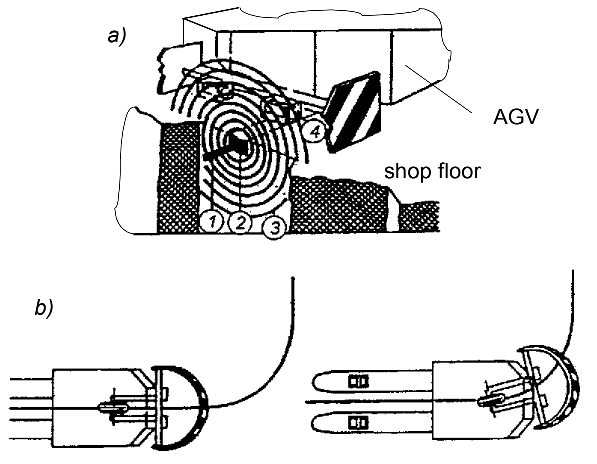



Fig. 8.10. AGV wire guidance: a) principle of wire guidance: 1 – in the floor embedded energized wire, 2 – groove, 3 – electromagnetic field, 4 – induction coil, b) path tracing

There are many patterns of AGV guidepath: open in-line, open branched, closed loop and webbed (many loops connected in a net). By webbed guidepath in each loop is other current frequency (Fig. 8.11). The selection of path thereby follows through the recognition of given frequency.

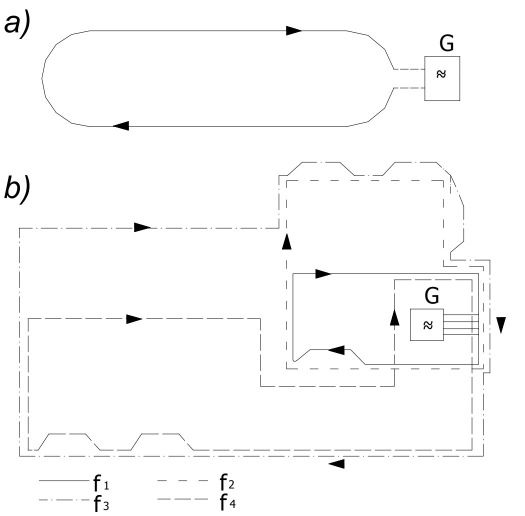



Fig. 8.11.
Current supply of wire guidepath: a) closed loop - one frequency, b) webbed - several frequencies, G – generator, f - frequency

AGV moves on programmed running path. The travel program may be initiated manually, by pressing the button "drive", or remotely through the transport system control dedicated computer. In such a case, the orders for AGV are transmitted through the induction wire. Along the running path, there are placed stop-points: steady and alternating. Magnets in the floor usually indicate the first ones, whereas reflecting foils the other. They are locates at workstations, internal part queuing, stores etc. At the stop-points there may be initiated the following special programs:

- Automated the pallet back-up,
- Reversing and automated the pallet taking up,
- Automated drive of conveyor, handling the load onto the truck, or undertaking the load,
- Automated disconnection the trailer coupling.

Carts are propelled by electric motors that are powered by industrial-grade, lead acid storage batteries (Ni-Cd) mounted in the AGV. They typically have a normal charged cycle life of around 20 hours. Then the cart must be routed to the AGV maintenance area for battery recharge or replacement. Battery replacement must be done manually, but recharging can be done either manually or automatically. Some carts can be programmed and routed to plug themselves in for recharging when battery power becomes low.

Many safety features are available on AGV. Some of the more common include:

- Yellow caution beacons mounted on the front and back of the cart that flash when the cart gets ready to move and that continue throughout the move,
- Audible, multiple-pitch and adjustable warnings signals,
- Safety brakes on each drive wheel that automatically engage when the power is off,
- Emergency stop buttons on each side of the vehicle,
- Impact-sensing safety bumpers on each end of the vehicle that stop the cart when minimal contact and bumper compression are made. Initiating the cart travel again requires service intervention.

AGV may be integrated with an industrial robot realizing the manipulation tasks by loading and unloading of workpieces, or tools. (Fig. 8.12 [49]). Such a cart is also called a *self-propelled robot*.

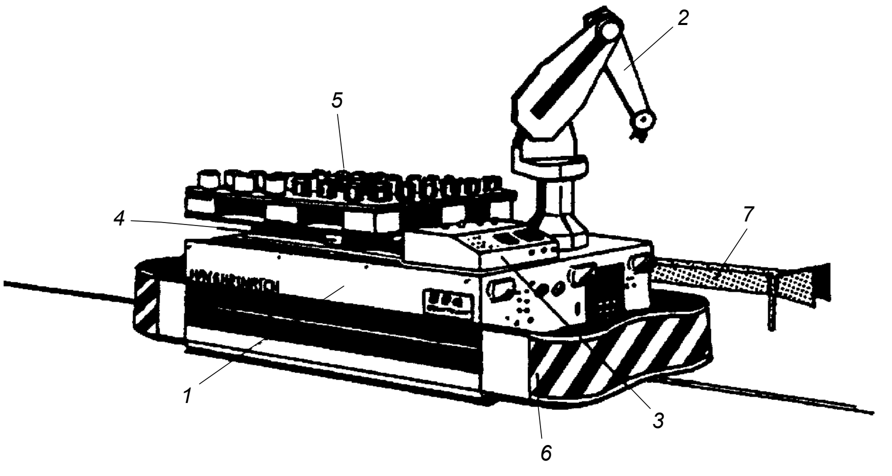



Fig. 8.12. Movable robot mounted on an AGV: *1* - wire guided AGV, *2* – industrial robot, *3* - robot control unit, *4* - rotary index table (4 x 90 0), *5* - pallet, *6* - safety bumper, *7* – power supply connector

The AGVs characterize the following advantages:

- Short installation time,
- High flexibility by FMS layout change,
- Easy access to machine tools due to lack of any bearing and rail structures,
- Favorable, with respect to industrial safety, smooth driving floor surfaces,
- Unnecessary shield structures,
- Space economy (there can be utilized normal communication ways),
- Easily adaptable to increasing transport needs by increasing the carts number,
- Not-blocking of transport path by cart failure,
- Good traffic safety (small accident expectation).

To their disadvantages may be included relatively high price and some problems with accuracy of docking at loading/unloading stations.

The transport systems realizing the rigidly stated guidepaths characterizes only limited flexibility. The tendency to increase flexibility of system led to appear the concept "free programmable running path" (virtual guidepath) [37]. Problems, which in such a case arise, are associated with inaccuracy of driving mechanisms and with variability of surroundings (e.g. incidental unevenness of floor surface, or other obstacles as left of containers, loads etc.). They may lead to deviation of programmed running path, or to collision. Right realization of transport task requires than watching and possible correction the movements of vehicle. One of possible solutions is continuous supervision by way of observation through the watching system the entire surroundings in which the vehicle is moving. There may be used here vision, laser, or ultrasonic systems. Such solutions, which require processing by the onboard computer, high number of data, are not necessary in flexible machining, assembly, or storage systems, which layout are not often changed, and distances between workstations are usually not great. In such a case, it is sufficient to place in the programmed area of vehicle path some "reference points" and check whether the vehicle moves on proper path (Fig. 8.13)

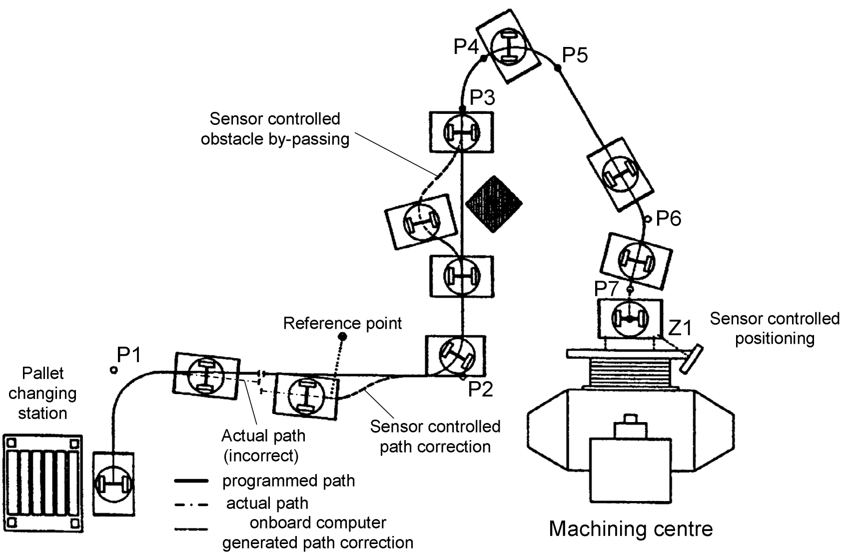



Fig. 8.13. Realization of programmable AGV guidepath

The reference points are placed with the purpose to check the longer straight lined path sections where the danger of significant deviation of exists given running path. Correction of path, omitting obstacles and positioning by docking at the workstation is made with the use of ultrasonic sensors. The ease of changing the direction of running what is necessary by omitting the obstacles, or by precision docking, requires particular properties of truck driving system.

### 8.2.3. OTHER TRANSPORT SOLUTIONS IN FMS

1. Gantry robots

They find still broader application in FMS, not only for part handling (loading and unloading). But also to realize many another functions associated with the material flow, as e.g. work-holding and work-changing, tool heads changing, and also fixture assembling and part clamping on the pallets (when the weight of devices and parts exceeds 20kg) or part handling in the assembling systems. In case of lathes the use of linear gantry robots is much more convenient than the industrial robots (with arm), because they do not block the access to the machine tool. Besides of linear robots, there are also used “gantry surface robots”, which in convenient way may service several machine tools, and realize transport tasks.

2. Stacker cranes

The basic task of a stacker crane is to service the storage racks. They fulfill the transport functions in the frame of this task. In some solutions of flexible manufacturing systems of linear structure, the stacker crane may also realize transport between the workstations. E.g. in the system FFS 500 of WERNER [11] the stacker crane servicing the central FMS tool store, makes the transport from this store to all workstations and does the tool exchanging in the tool matrices.

3. Industrial robots

They find main application in machining cells and in plastic working (sheet metal forming). The robot servicing the machining cell is located in a central place and may realize the transport operations between particular machine tools in the cell.

4. NC overhead traveling cranes

In the transport of materials, in the automated manufacturing system may be also used numerically controlled overhead traveling cranes. Such cranes ensure realization of all transport tasks, that means both the transport of workpieces and tools, as well as transport tasks of auxiliary processes. The advantage of this solution is that the transport is fully independent of the manufacturing system layout. It is then possible optimal location of the workstations and also free change of their placing without interfering in the transport system.

The disadvantages of this solution is the low transport speed, poor accuracy of load positioning, and also impossibility of parallel realization of transport tasks, as it may take place e.g. in case of cart transport and simultaneous operation of several carts.

# 9. INFORMATION SYSTEM

The information aside of transport subsystem is the second functional system linking and integrating under central computer control all the facilities to flexible manufacturing system as a whole. It realizes many functions enabling this integration. The main goal of information system in FMS may be recognized as follows:

*Minimization of idle machine times and shortening of production order realization time.*

Functions, which realize the information system of FMS, are presented schematically on Fig.9.1.

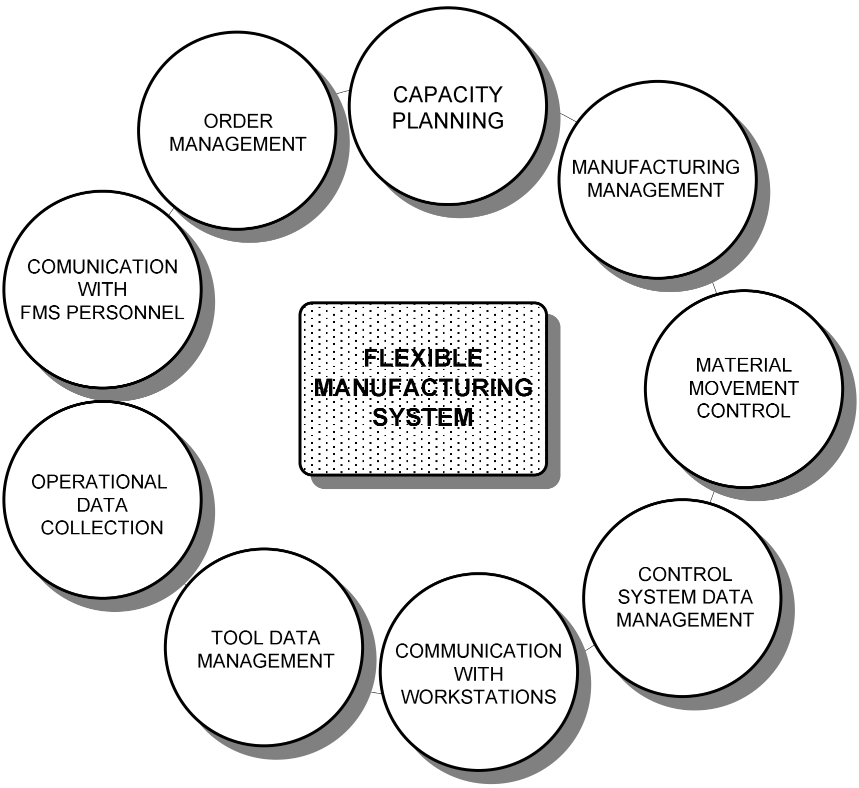



Fig. 9.1. Functions realized by FMS information system

All these functions may be grouped in two main functional areas (Fig.9.2).

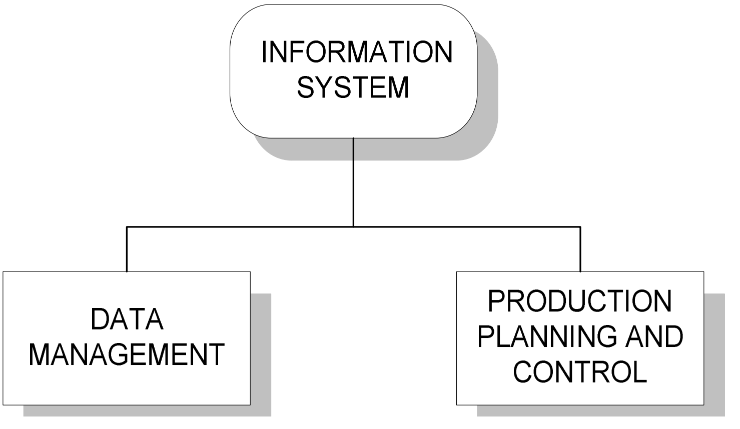



Fig. 9.2. The main functional areas in FMS information system

## 9.1. DATA MANAGEMENT

The data management includes acquisition them in database and in case of need retrieval accessible all data associated with planning and control of part machining in flexible manufacturing system.
Actually, there are used four basic database models:

- Hierarchical database,
- Network database,
- Relational database,
- Object-oriented database.

Application of database may be of single-stand, or multi-stand. Bases belonging to the first mentioned above types consist of data set and set of functions, operating of them, implemented on one computer. Operator has the possibility of manipulation in area of all data. Such architecture does not allow using the base simultaneously by many users. This limitation does not possess multi-stand bases, allowing for simultaneous operation. The multi-stand bases may be organized according to different structures. Out of them, there can be distinguishing the following architectures:

- Central database
- Client/server database
- Distributed database.

At the present stage of development of computer assisted production processes, the database fulfils the function of interface between various spheres of enterprise activity. This is associated with very large data sets, with simultaneously high requirements regarding the access time, and data security. The majority of systems are based on relational database first of all because of the ease of adaptation to changing requirements. In case of quick access to data and quick data processing necessity at ensured simultaneously the use of resources by users working in the network, the most commonly widespread configuration of data bases are client/server architecture. The most important criterions by choice of database management system are the following [5]:

- Use independence,
- Integrity of data resources,
- Possibility to secure the data,
- Data compatibility,
- Integrity of new data.

The difficulty in the access and utilization of data used in the production systems is, that they often are in bases of various independent from itself computer aided systems. It is also the cause of enterprise model redundancy. Therefore, there exists a tendency to elaborate a platform integrating the use of information technology in the enterprise, from planning the manufacturing system, through the product development, to the production process, with consideration of the cost account, or e.g. training the personnel (Fig.9.3).

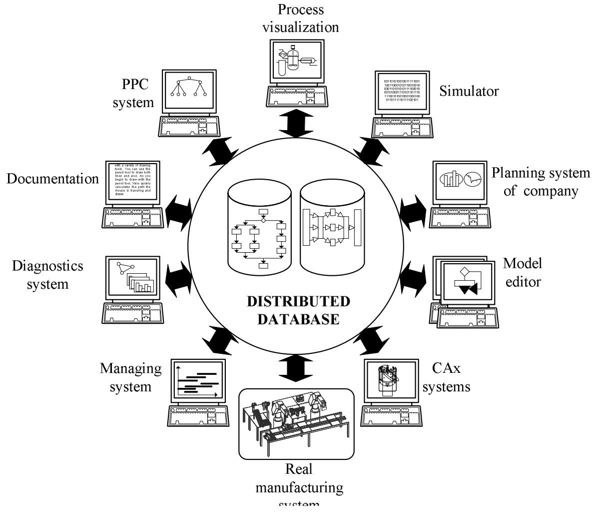



Fig. 9.3. Platform to integration of all computer aided applications in a company - company data model (according to [39]).

Such an integrated model of enterprise data would allow also for better utilization of simulation techniques in planning and operating of production systems and also for decreasing the simulation costs [39].

## 9.2. SHORT TERM PLANNING AND CONTROL OF PRODUCTION PROCESS

The second functional area of FMS control system is the *short term planning and control*. The realized aim in this area is a detailed defining the production process progress in the existing system, whereas the basic task of short term planning is (according to [38]) cited after E.Chlebus [5]: *systematic searching, classification and defining the production tasks and means to reach the stated aims*.
However, the main task of production control is [38]:

*Starting, monitoring, and ensuring the realization of production tasks, considering the quantities, terms, quality, costs and working conditions*.

Activities realized in the computer aided system of planning and control of production process - PPC (Process Planning and Control) are depicted in Fig.9.4. The initiating point in the sequence of these actions, are data referred to production orders and terms of realization, given by the plant host computer. They allow defining the kind and quantities of parts to be machined in the system and to state the earliest time points in which should be ready the semi products and materials, and the latest acceptable terms of realization the complete machining of all the parts.

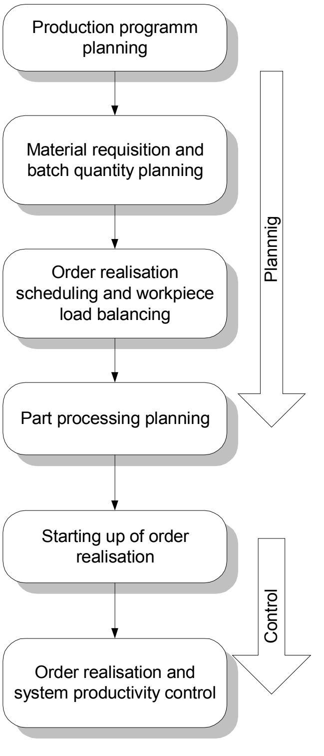



Fig. 9.4. Activities in operational (short time) planning and production process control

Planning the material demand and product quantities in a batch, are contained in a short term planning of production program. To enable production of defined product quantities, there is the necessity to know the quantities to purchase, or manufacture, material, assemblies or elements. These are carried out based either on product documentation or on the data of use in the past. Determined in the way material demand is in turn divided into production batches (or ordered batches) during the batch number determining. The criterion is a balance of costs of storage, and rearranging the system, taking in consideration the use of these materials, and the existing stock on hand.

After the acceptance of orders and planning the material demand, there follows creating and structuring the routing of workpieces to be run through the system and to manage, control, and dispatch workpieces and resources within the FMS. All processing steps must be listed in sequential order, and the resources to be utilized, such as part programs, cutting tools, and fixtures, must be available and accessible.

Work-order preparation must be completed well in advance of the part's scheduled run time. Any workpiece introduced into an FMS must be identified to the system by means of work order. Identification of each workpiece type generally includes defining the number of parts to be processed, start date, due date, and routing sequence. Work orders must then be authorized by the system manager for processing activity to begin.

In the flexible manufacturing system, there can be simultaneously realized many productions orders, by different batch number. However, thanks to the fact, that FMS is functioning as one, integral production unit, the process of planning is in this case much simpler. Taking in consideration one point of view, the above-mentioned variety of realized in parallel orders it should be affected with increased complexity of planning and from the other side there are many factors, which this complexity diminish:

- In FMS are used mainly the machining centers which integrate the functions of many conventional machine tools, what in comparison to conventional manufacturing, markedly decrease the number of objects which should be considered by planning the material flow,
- The use of centers causes also decreased the number of part machining operations,
- Informatics association of automated manufacturing installation enables better acquisition of processing data and also improves the topicality of planning data.

The presented here tasks of informatics system are realized by the FMS control system. This system includes the data flow both between the workstations and other installations of FMS which realize functions associated with running the manufacturing process (strictly, between terminals or controllers), as well as between these units and surroundings. Actually, it consists usually of a number of autarchic sub-systems realizing various tasks (see Fig.9.1). These sub-systems create a hierarchic structure, which is characterized by the fact, that it enables further work at limited time by systems situated below in the hierarchy in case of failures at highest levels. Such a structure facilitates also the development of the manufacturing system.

The main functions in this matter, associated with the current production control, are referred to the planning of sequence of manufacturing operations. The realization thereof may be made in cycles in three subsequent phases:

1. making a daily timescale of initiations for lots of particular products,
2. assigning operations to isolated groups of workstations exact to working shifts, and preparing time schedules for:
   - Completing the machining aids,
   - Arranging of stations and pallets.

3 – Detailed determining the sequence of production operations; the result thereof is the operations timescale of different flexibility level:

   - Timescale of basic flexibility level, which define the terms of beginning and ending operations on particular stations, taking in consideration also the stations which realize the auxiliary works e.g. the transport cars,
   - More flexible time scale defines sequence of operation, without defining the term of beginning and termination,
   - Timescale of the higher flexibility level is defined in the form of set of rules characterizing servicing of the queues arising by particular workstations. These rules are the basis for current sharing of operation between workstations. They are determined for a defined production task according to the accepted criterions (e.g. maximization of the workstation utilization, minimization of breaks in working of the most loading stations).

The other functions of the control system are the following:

- Dispatcher function: assigning the operation to be made, for defined stands,
- Distribution of control programs,

- Monitoring of realization progress of particular work orders,
- Recording of the part (and other displaceable resources) flow,
- Inspection of equipment operation condition,
- Reporting,
- Running the statistics,
- Communication with other systems of enterprise.

## 9.3. CONTROL SYSTEM ARCHITECTURE

There are two basic types of production control system structure: *centralized and decentralized*. The *centralized systems* show a range of non-advantageous properties such as: relatively high installation costs due to complicated and expensive parallel wiring system, high sensibility to failures and external influences, limited possibility of remote defining the parameters of installations (e.g. motor drive controller) due to lack of appropriate communication network, difficulties and costs associated with modification or expanding the system. Due to these reasons, the advantages actually gained by the decentralized systems are, defined also as the "system of a second generation". The decentralized control system consists of arrange of computers and terminal installations, making in parallel various prescribed them functions (Fig.9.5).

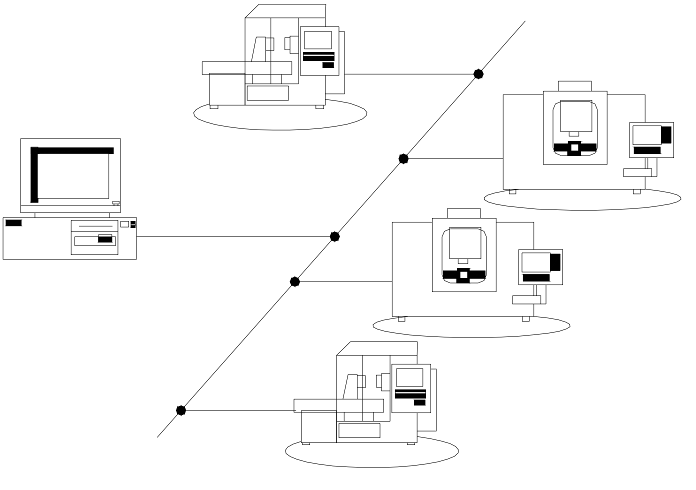


Fig. 9.5. Architecture of FMS control system - decentralized computer environment

These can be computers monitoring the operations of workstations and other FMS equipment, as well as special dedicated units, e.g. computer of the operator of FMS realized computer aided planning of the production progress. Despite the possibility of communication of all computers between themselves, often to one of them is prescribed the function of communication processor. It results from the fact, that the majority of messages emitted by particular computers and especially these out of them, which monitor the working of FMS, contain data referred to many other tasks making by the remaining computers. The role of communication unit is in this case limited to analysis of messages, selection of their content from the point of view of receivers needs, and the degree of data urgency and also resulting messages formatting and their emissions according to defined priorities. In this way, the remaining computers are relieved from functions associated with the data distribution. An additional advantage of such a solution is the higher flexibility thanks to facilitation both the possible changes of hardware and software configuration resulting from the changing of production structure of FMS and changes of the range of functions made by particular programming modules, changes of data formats, messages etc.

The decentralized systems are an example of realization the distributed data processing idea. In particular, they enable the use of distributed data bases. The local computers manage the data of local importance. It limits the range of transmission of data, but on the other side, it shortens the time of access to data necessary to fulfill the local tasks. Beside of this, such a system ensures the greater freedom of selection the moment of data transmission. The majority of them do not need to be made immediately, but it may be realized in the periods, when the computer does not make the time critical tasks.

Building of decentralized production control system in FMS is based on the use of specialized, industrial communication fieldbus network, such as e.g. "Profibus", "Interbus", to which the particular, distributed on the object, peripheral automation devices are interfaced. These networks are featured by a great transfer function and quick transmission of data with simultaneous simplicity of connections realization, and low execution costs.

There is recently observed significant growth in importance of the Industrial Ethernet communication network in manufacturing systems.

The whole of the control system of a developed FMS creates a hierarchic structure in which there can be distinguished four levels (Fig.9.6):

1. The highest level of the system control and monitoring of the realized manufacturing process state,

2. Plane of direct monitoring of machine tools and other NC equipment operation; within this plane may be also situated computer which controls the quality of manufacturing,
3. Plane of the machine tools and other NC equipment control,
4. Plane of sensors and functional elements of machine tools and equipment,

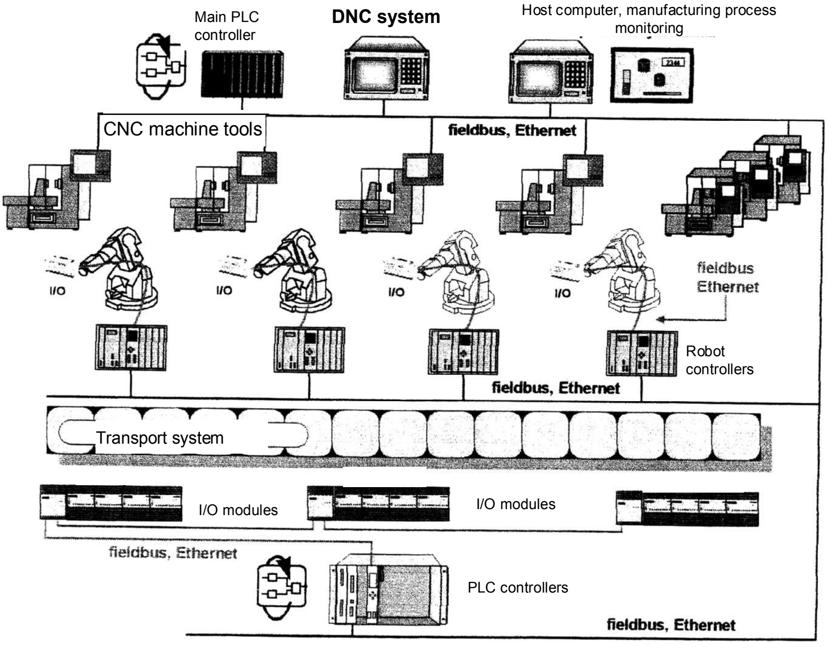



Fig. 9.6. Structure of FMS control system

The system includes:

- Host computer,
- Controllers of machine tools, manufacturing equipment, robots etc.,
- Digital and analog sensors and executive elements, motor drive controllers, control panels, control devices, counters etc.,
- Communication system.

The higher level of system control, that is first of all the host and DNC computer. The main task of host computer is the realization of works associated with operational planning and production process control, and also initiation, during the unmanned system operation, the alternative strategy of proceeding in case of failure of one of the machine tools in FMS. In case of such a failure, the host computer should be provided with replacing machining programs, for remaining in tact – machine tools, and eventually, it should be followed switching to machining other parts, or at last interruption of working.

Under the DNC (Direct Numerical Control), there is means the system of control of a group of workstations, such as the NC and CNC machine tools, coordinate measuring machines, robots and other. In the original concept, actually no more used due to low effectiveness, the DNC computer fulfils the function of controller of all connected to it installations. The appearing of microprocessor CNC systems equipped with high capacity memory caused a total change of the working character of DNC computer. Actually, its basic task is the management of part machining programs in FMS. Besides, the DNC computer transmits programs to other NC installations, such as coordinate measurement machines, part manipulators, robots etc. It also transmits the data referred to tooling (corrections, tool life) and orders to operators (pertaining to the schedule of part fixing on pallets).

The additional task of DNC computer may be also included the collection, processing and transferring the machine-using data and if it is not fully used, what often takes place, may be used for other purposes e.g. for programming.

The following functions belonging to the management of machining programs (according to H.Kief [41] are as mentioned below

- Receiving the machining programs; the new-ones from the programming system, and the used-ones from CNC,
- Collecting data in appropriate mass memories,
- Management of NC programs according to defined criterions, e.g. required memory capacity, demand on the tools, machine tools on which the program will be realized etc.,
- Transferring the machining programs to the machine tools in appropriate time,
- Making copies of machining programs to secure them against any losses,
- Comparing the programs transferred back from CNC, to the original ones and revealing the changes made,
- Blocking the transferred programs from CNC until releasing them by the programmer.

Transfer of programs is made in the following way:

- In double direction, from DNC to CNC and reversely,

- Semi-automatic, that means the manual calling by the operator, or automatic i.e. without the interference of operator,
- With the protection, i.e. by checking the correctness of transmission with automatic correction through repeating the transmission by appearing an error,
- With receiving the correction data and managing correction of tools (data are coming from the tool room, or from CNC by exchanging the tools in the tool matrix; correspondence with the stand of preliminary tools setting-up my be carried up manually or automatically,
- With individual set-up of transmission speed for each attached CNC controller.

Under the term *central gathering of machine operational data*, there is means the collection of necessary, actual data from the area of manufacturing, and transferring them in the form suitable for processing, to the system of operational planning and control of the production process in order to designate the new input data for the costs calculating and materials management. The work covers, between others, the following:

- Recording the working time and standstill,
- Statistic analysis of recorded data, according to number of machined parts, number of spoilages, times of failures, time of standstills caused by awaiting,
- Central reporting of disturbances (errors), monitoring of machine tool, service and inspection orders,
- Loading the data on optional information carrier.

### 9.3.1. MACHINE TOOL AND MANUFACTURING EQUIPMENT CONTROLLERS

The main components of FMS control system belong to NC and CNC controllers of particular manufacturing equipment and first of all machine tools. NC (Numerical Control) is a program control, which covers with its program - beside of sequence of movements in NC axes, machining parameters – also all geometrical data (coordinates and displacements) necessary to define the position of tool in relation to the workpiece. By realization of a complex relative movements of tool and workpiece, the control systems are provided with the interpolator, ensuring such a control of movement in two, or more NC axes, so that the resultant relative movement of tool and workpiece between two consecutives points of given coordinates, were carried trajectory which depends upon the type of interpolator (e.g. linear, circular, parabolic, or mixed).

The control systems using the computer have the name CNC (Computerized Numerical Control). The CNC system contains a processor and memory of a capacity capable for one or more part machining programs. Functioning and application possibilities of CNC are resulting not so much of its structure, but of software used. The rational division of functions between the hardware and software in the systems of CNC ensures lower costs, compactness, high flexibility and operating speed, ease of expansion and adaptation to defined use, maintainability, operating comfort and high reliability.
Actually, often find application the CNC based on industrial PC computers (Industrial Personal Computer).

The flexible manufacturing automation requires from CNC controller possibilities in the following areas:

1. *Memory capacity*

First of all it‘s necessary, to have the possibility to store in it possibly many part programs, what makes the machine tool independent from the DNC computer. Besides, an adequately great area of RAM memory is necessary to store sub-programs, technological tables (tool correction data, displacement of zero point, dimensional correction due to tool wear, tool life tables etc.). Non – variable data pertaining to control system are stored in the EPROM memory, whereas data referred to the machine tool and other seldom changeable, in the EEPROM.

2. *Data management*

The organization of data management should ensure the machine tool operator an easy access to it, in order to check the resources, manual searching of programs, their activation, erasing, correction, securing against changing etc. There should be also ensured the possibility of visual and automatic inspection, through the host computer of free memory capacity in order to check whether this capacity will be sufficient to introduce next part machining program. The execution of the above actions should be possible within the mean time of the machine tool, without interrupting the machining.

3. *Remote control* (by a host computer)

Such possibilities are necessary by a full automatic (unmanned) FMS operation. Then the host computer must have the following possibilities:

- Bringing the tool to a reference point,
- Changing the operating mode,
- Starting the machining program,

- Automatic stoppage the machine tool in case of disturbances in working (failures).

A range of such data as the part machining programs, correction data, tooling data, data from the monitoring system should be transferred in both directions.

4. *External machining program calling*

If in the memory of CNC exist several machining programs, there must be possible to call appropriate program by the pallet code, or by the DNC computer, and to erase the useless program by this computer.

5. *Reporting of the errors and warnings*

Possible errors by data input or reading must be immediately captured and if possibly corrected by multiple input repeating. It refers both to the machining programs, as well as to correction data and shifting the zero point. The reported errors should be either in the form of error number, or by text information with a given data, hour, duration and possible cause, reported to the managing computer in order to record in the central error statistic.

6. *Acquisition the machine and operational data (AMOD)*

In the memory of CNC controller, are acquired the data about the reasons of disturbances in working and standstills taken automatically, or introduced by the operator. The system AMOD of DNC computer takes them over automatically with a frequency e.g. once per day, or once a week. The host computer, using appropriate programming, can automatically made the statistic of disturbances for each machine tool and manufacturing equipment.

7. *Tool management*

The task of CNC controller consists here mainly in optimization of tool spacing in the tool matrix (where big, over-dimensional tools occur), and on minimizing the loss of time in exchanging the damaged and worn tools for new in the machine tool magazine. It matters here of realization the action of "exchanging" during the machine tool main time (during the machining), and ensuring priority of changing the tool in the spindle. The range of duty increases in case the machine is equipped with exchangeable tool cassette.

8. *Pallet management*

The need for the pallets (machining parts) management appears first of all in the closed-loop FMS systems, because the host computer cannot practically control their actual positions. The CNC control checks then the code of the pallet and decides about accepting it for machining, or send it further. When operating in the unmanned system, there additionally appears the task to determine the priority of machining of various parts being in circulation.

9. *Controlling the measurement cycles*

The application of measurement probe on the machine tool requires that the CNC controller would have programmed measurement cycles (Fig.9.12) and programs for data processing at its disposal.

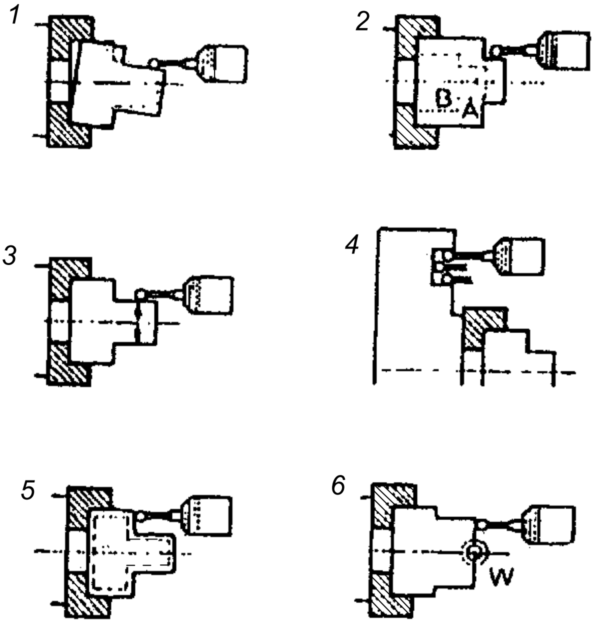



Fig. 9.7. Example of measurement cycles realized using touch probe: *1* - incorrect part clamping detection, *2* - part type identification, *3* - part measurement before, during and after machining, *4* - compensation of thermal deformation, *5* - allowance identification, *6* - defining of zero point on the part

Out of these data should be calculated such quantities as:

- Coordinates describing the part position in reference system,
- Boundary values of dimension and allowances,
- Diameters of holes and riser heads  (in castings),
- Lengths and widths of grooves,
- Correction of zero point,
- Correction of tool wear,
- Compensation of part fixing allowance,

- Tool dimensions.

10. *Protections against exceeding the workspace*

Errors of programming, or reading in may lead to exceeding the tool beyond the machine tool workspace. This may cause collision and in consequence tool damage. To avoid this, each of NC axes – X,Y,Z – must have a kind of program end switch. The movements of tools are then possible only in certain allowed, limited space. Appearance in the machining program the tool position beyond this area causes stoppage of the machine tool and reporting the error.

11. *Ensuring the possibility of use the test mode on the machine tool*

This is necessary by testing the new part machining programs. Such as a practice may contain a range of particular conditions given in a rigid way, or optionally, as e.g. blocking the movements in respective axes, blocking the execution of auxiliary and switch-over functions, increasing the feed, actuating sub-programs and cycles etc.

12. *Automatic correction of tool wear*

The tool wear, especially by turning and boring, is a constant factor influencing the machining accuracy. Therefore, it is desirable that considering it, take place automatic, independently of data input of other correction values (Fig. 9.8).

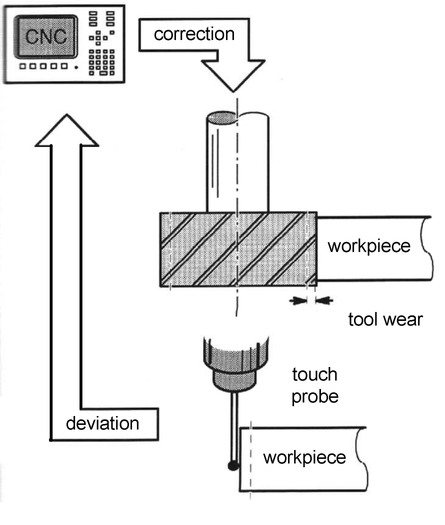



Fig. 9.8.Automatic tool wear correction

13. *Communication with DNC system*

Each of the CNC controllers in the flexible manufacturing system should have the possibility of connection with DNC computer, whereas communication may take place directly from the CNC keyboard or with the use of additional terminal. This connection should ensure suitable speed of data transmission.

14. *Control of additional NC axes*

Many of NC machine tools are equipped with additional NC axes besides of these, which are directly connected with the part machining (part shape creating). They are used to handling (during machining) the tools and/or the machined part. Their programming is independent from the machining programs. Application of such NC axes gives additional possibilities such as optimization of speed of movements connected with the tool exchanging. In case of big and heavy tools, these movements may then be slower than by small and light tools faster.

15. *Diagnostics of disturbances*

In case of machine tools of a complex functional structure, this function of CNC control is necessary to determine quickly and securely the causes of disturbances resulting in standstills and work interruptions. Thanks to a special programming, the screen is changed into oscillograph with a memory, enabling the graphical presenting registered values and storage them. It is expected fulfilling of the following diagnostic functions:

- Drawing theoretical and real movements trajectory in particular NC axes,
- Visualization of dynamic behavior (time characteristic) of NC axis,
- Drawing (multi-channel) of control processes time running (switch in/out) with selective time scale,
- Recording of all warnings and reported errors,
- Recording of all “manual” interferences (the data inputs).

Beside of CNC in machine tools and other manufacturing installations, to the basic components of FMS control system belong the programmable controllers PLC (Programmable Logic Controller). The development thereof resulted in the possibilities to take over still more complex control functions. Their advantage is a simple and hence quick solving the control task. This gives the time saving by planning, changes and optimization of these tasks. Further, their advantage is a compact structure of small overall dimensions and ease in this way of embodying in various controlled devices. The possibilities being actually to the disposal of PLC that means making calculations, data comparison, analog data processing, automatic disturbances diagnostics, are resulting in very effective elements of flexible systems control. Thanks to its possibilities and advantages, the PLC Controllers are used (instead of computers, especially in case of less developed systems) to control the transport system operation, the store, or also industrial robots.

## 9.3.2. TRANSPORT SYSTEM CONTROL

An important role, due to integral function of the" transport system", plays control it. It receives the orders from the host computer (or DNC). Depending on the accepted solution of part transporting and associated with them control complexity, it may be based, in simple cases (e.g. in closed-loop systems) on the use of PLC controller. In a more complex (e.g. in car transport), it may require a dedicated computer having information about an actual FMS state, i.e. a full information about position of each pallet. The function of part flow control, may also realize the DNC computer. The range of tasks to be solved by the car system and control thereof is the following:

- Recognition of a machine tool with free input station (i.e. one of parts is being machined, and on the output place one part is already finished),
- Checking the given priorities in case when several machine tools are simultaneously called the readiness state,
- Transporting the pallet with appropriate part from pallet storage, or fixing station, to the machine tool,
- Drive to the machine tool, docking and changing the pallet, i.e. taking away the pallet with ready part and leaving a new one on the input station,
- Checking , whether the wash-station is free,
- Drive to the wash-station, leaving the pallet with the part to machining and taking away the washed part,
- Calling the readiness of the car to the next working cycle realization.

## 9.3.3. COMMUNICATION SYSTEM

The areas of application of communication systems enclose all levels of production organizational structure: from managing the enterprise, through production preparation, operational production control, control of the manufacturing system operation, controllers of machines and installations, until the level of sensors and execution elements (Fig. 9.9).

On the levels of enterprise management, production preparation and operational control, there dominate the problems of transfer a great number of data with complex structures. In these areas, more important role plays the capacity of communication system, then the speed of data transmission. There are used in them wide and local computer networks (WAN - Wide Area Network, and LAN - Local Area Network).

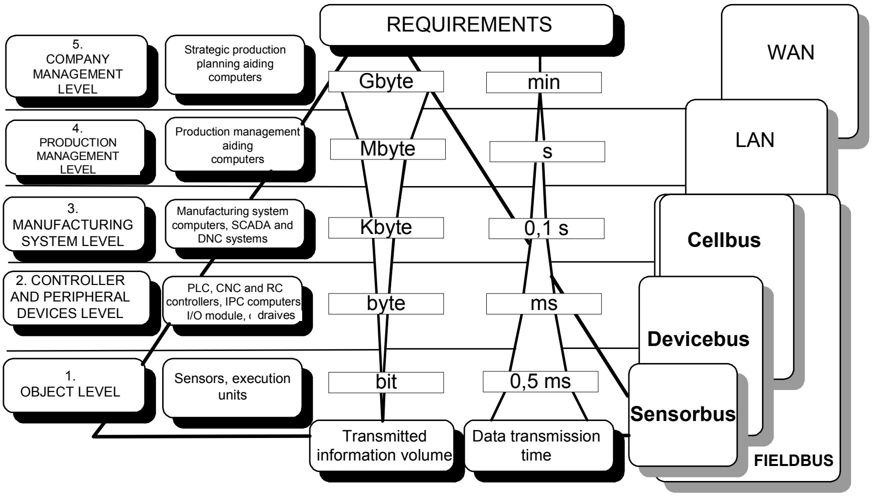



Fig. 9.9. Application areas of communications networks and suitable requirements

On the level of manufacture system, there are used solutions made for local networks LAN, such as the *Ethernet*, or *Fast Ethernet*. Beginning from this level, there are used industrial networks buses called "*fieldbus*", such us *Profibus*, *Interbus*, *Device Net*. They enable transmission of data in the real time. This notion (real time) referred to the response time of system to information about an event occurring in its surrounding, should be understood in a relative way with respect to the speed of the process control running. In practice, the industrial communication systems, such as *Interbus*, or *Profibus* are transmitting data within the time of 1 to 30 ms and for communication in the area of sensors and executive elements (e.g. network ASI and *Interbus Loop*) within the time from 0,5 to 10 ms. Model of communication system in an enterprise is actually based on the three different networks: in the lowest level of sensors and execution elements on the network ASI (*Actuator and Sensor Interface*), or *Interbus Loop*, in intermediate level of peripheral automation and control devices on the network *Profibus* or *Interbus*, but on the highest level to connect the controllers of devices with higher-order control and monitoring system on the *Ethernet* network. Actually, thanks to development of the elements (concentrators, network switches) of *Ethernet* standard, it became possible to use it also on the lowest levels of communication systems, which require transmission in the real time [45]. It enables to substitute the hierarchic pyramid of *fieldbus* network by a flat communications structure with integrated *Ethernet* network and TCP/IP protocol.

The communication interfaces of different network solutions are specific with respect to their manufactures and due to that fact they are significantly non-compatible between themselves. This is the reason of significant costs by integrations of different automatics devices. Therefore, the international standard organization ISO has prepared in a form of a standard (ISO 7498), and published under the name of OSI (*Open Systems Interconnection*), a reference model used to realize open, and hence independent of the manufacturer communication interfaces. The reference model makes the frame specifications describing conception of a hierarchical structure of communication system, which enables creation of opens communications interfaces. It defines the open systems, their cooperation in the surrounding of OSI, and the layer model (Fig. 9.10). As open are meant systems in which take place information exchange in accordance with the communication standards based on OSI reference model.

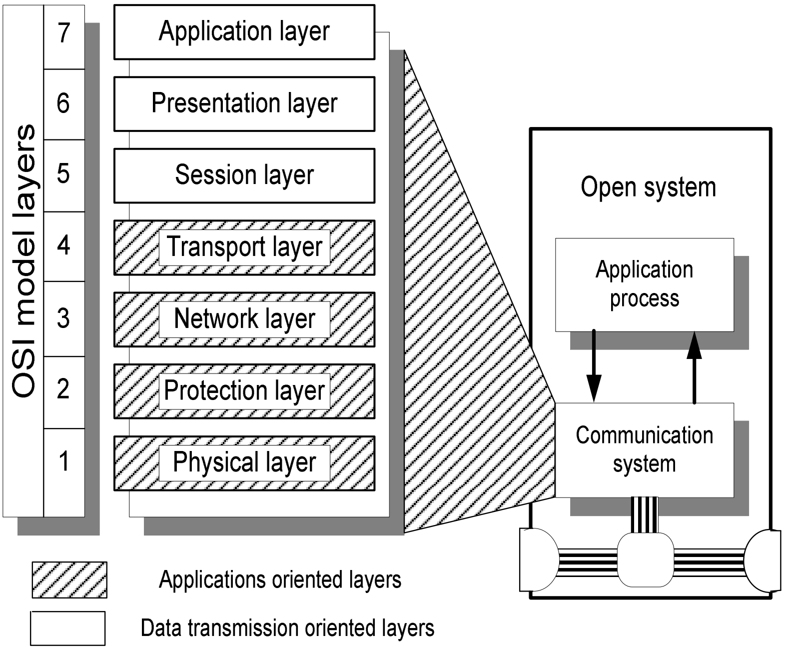



Fig. 9.10. The OSI reference model

The open system has been divided into two main parts, strictly separated of each other, named:

- Application process, and
- Communication system.

The application process is a part of a system carried out the data processing for a defined use. The communication system enables, by means of physical data carrier, information exchange with another open system. The rules, according to which the exchange of information is carried out, are named *protocol*.

The OSI reference model covers the tasks, which has to fulfill the communication system in seven layers:

1. Physical layer

   In the layer there are determined details of information transfer between open systems, such as methods of modulation or coding, or else electric properties of medium transmitting the data. The function of this layer is to ensure the flow of non-structuralized stream of information bites.

2. Protection layer

   This layer contains mechanisms, which ensure correct transfer of data in the form of blocks of information bites. It monitors the access to physical information carrier, defines the addressing system and enables the data flow control.

3. Network layer

   Whereas the first two layers ensure the correct data transfer on the same segment of information carrier, the functions of network layer enables the information exchange between two open systems by the use of different segments, with the use of interface devices (e.g. the routers). It chooses the transport path and addresses the datagrams.

4. Transport layer

   This layer based on the network layer functions enables stability of connection between optional application programs in open systems. It ensures the continuity of information flow.

5. Session layer

   It ensures realization of functions necessary to begin, correct carrying out and finishing of communication connection, called the session.

6. Presentation layer

   It enables realization of different methods of coding, visualization, forming, or else conversion of exchanged information.

7. Application layer

It is directly designed for application process and encloses e.g. passing on commands connected with realization of defined process.

The layers 1 to 4 contain together functions necessary for undisrupted information flow between application processes and therefore are described with a common name *layers oriented on information transport*. Layers 5 to 7 however are named *layers oriented on applications.*

Many standardization committees formulate, for defined communication tasks, their own OSI standards. Therefore, there actually exist over 100 different standards for seven layers of OSI model. When planning a manufacturing system, it should be then selected from existing standards those, which are suitable in the best way to specific application tasks. Such an action is called working out of assumption and technical requirements, an adequate to a specific application *profile* (called too *network architecture*) of communication system. The sets of standards created by selection suitable, specific for each of seven OSI model layers, are called *functional profiles*. Actually, there are on the market many communication profiles, whereas the local networks have full profiles consisting of all seven OSI layers, the networks *fieldbus* type have communication profiles in principle only of three layers: 1, 2 and 7.

For use in the area of manufacturing technologies, have been formulated, yet not standardized profiles such as MAP, TOP and CNMA based on the OSI standards referred to particular layers of reference model. Standardized have been instead profiles for fieldbus communication. As examples there can be called: SERCOS for machine tools, Profibus, or DIN-Messbus. Under the acronym MAP there is the name of a project realized in American concern General Motors called *Manufacturing Automation Protocol*. This name suggests, that MAP is a communication protocol. In the reality, there are functional profiles based on OSI model. These profiles are:

- Full-MAP,
- Mini-MAP,
- MAP-EPA (*Enhanced Performance Architecture*).

Usually, under the name MAP, there is meant most often used Full-MAP profile enclosing all OSI model layers. Each of them is described by separate protocol. As a standard of exchange of MAP data, it uses exclusively Taken-Bus, and as means of information transfer, a concentric cable, or a light-pipe.

The use of the seven-layer profile is associated with significant prolongation of response time in the communication system. Due to this fact, for the area serviced by the fieldbus network, where there is required data transmission in real time, has been worked out a three-layer profile Mini-MAP covering the layers 1, 2 and 7. As a communication language in Mini-MAP is in use exclusively MMS (Manufacturing Message Specification). MMS defines the structure (syntax), and content (semantics) of information transference. This is a language designed especially for planning the open systems of manufacturing control. It has been standardized in the international standard ISO/IEC 9506 "Manufacturing Message Specification (MMS)".

The Profile MAP-EPA unites the remaining both, i.e. Full-MAP and Mini-MAP. This means, that the automatics device with implemented profile MAP-EPA may communicate themselves both with the systems using Full-MAP, as well as Mini-MAP.

The MAP profiles are assigned to the realization of tasks within the range of manufacturing systems. They do not consider the requirements of generally comprehensible bureaucratic area. Therefore, as a completion to the MAP, a profile TOP (*Technical and Office Protocols*) has been worked-out.

In the open control systems are also used communications protocols TCP/IP (*Transmission Control Protocol/ Internet Protocol*). Their arising is dated on the beginning of seventieth years of last century, when the *Department of Defense - DoD* of the USA has initiated creating of the first computer network. The communication system of this network has been based on the layer model, which can be recognized as an archetype of the later reference OSI model. Originated from the name of department of defense, it is called *DoD model*.

The structure of DoD model is based on four layers (Fig. 9.11). The open system in TCP/IP model, similarly as in the OSI model, is divided onto two parts:

- Application process and
- Communication system.

The layers 1, 2 and 3 are in this model oriented on information transport, and the layer 4 on application (application process).

The protocol IP ascribed functionally to layer 2 (internet) enables transport of datagram from any sender, by the agency of one, or many networks, to the receiver being in any target network.

However, the task of TCP protocol is to ensure undisturbed connection between two applications being in communication.

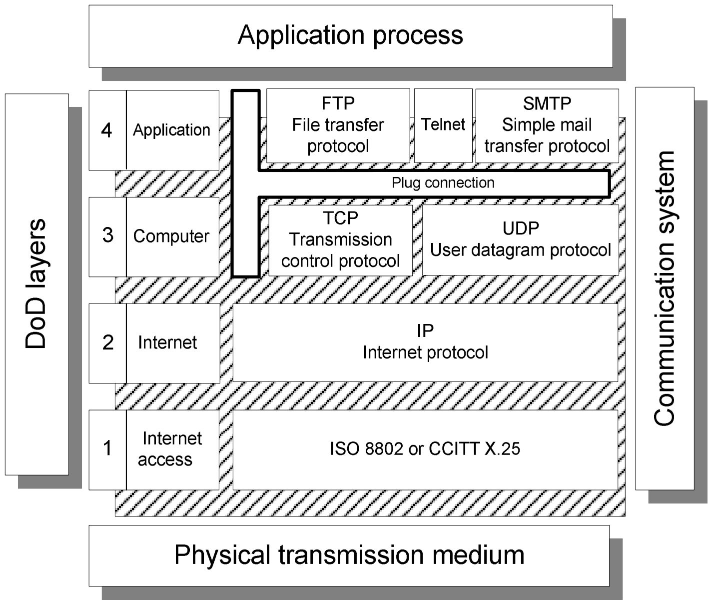



Fig. 9.11. TCP/IP model

In the application layer the most important protocols are:

- Telnet, for communication between terminals and interactive applications
- FTP (*File Transfer Protocol*), to file transfer, and
- SMTP (*Simple Mail Transfer Protocol*), for servicing the electronic mail.

# 10. MONITORING AND DIAGNOSTIC SYSTEM

Operation, especially unattended, of automated manufacturing system, is not possible without appropriately developed *automatic monitoring and diagnostic* system. M.Szafarczyk [51] defines the monitoring as "…*control, consisting in affect in order to obtain a desirable state despite disturbances, and if not possible to obtain the state least undesirable*" (cit. [26]).

The *diagnostic* encloses the detection of given inefficiency and determining their cause. However, as can be seen on the functional plane, there can be differentiated the tasks of *monitoring* and *diagnostics* but is in practice realized by one system.

The main goal of this system is:

*„Achievement of required manufacturing accuracy and assurance of high system utilization rate in appearance of disturbances".*

To realize these purposes, the system of monitoring and diagnostic influences the working of manufacturing system. These actions may be of direct or indirect character. In the first case it is understood, the reaction of the system control, however in the second case the transfer of information to the system staff and using it by planned, periodic survey, or by immediate removal the results of failures and returning the efficiency of the system.

In case of a machine tool, M.Szafarczyk (cit. according [26]) quotes the following forms of direct acting, with which one can have to do:

1. *Machine tool stoppage* - the simplest and most radical action
2. *The part program changing* - it results in automatic adaptation of machining tasks to actual technological possibilities, changed e.g. due to damages
3. *Correction of tool setting-up* - aimed to eliminating, or diminishing of the disturbances influence on the machining accuracy
4. *Changing the tool trajectory* - it can take place in case of form-closed control
5. *Changing the movement speed* - e.g. the feed or spindle speed, made with the aim to change the cutting parameters
6. *Compensation* of disturbances influences
7. *Exchanging the elements unable to work, into efficient one* - e.g. exchanging the worn-out tools.

There are three monitoring systems types:

- Protective

- Corrective
- Optimizing.

*The protecting system* prevents failures (serious damage causing breaks, or disturbance in manufacturing process). The protecting system includes diagnostic system detecting the appearing irregularities, e.g. the wear, or damage of tools.

*The correcting system* maintains the selected values in determined, allowed range. It functions based on measurement of disturbances or part machining results.

*The optimizing system* automatically changes the process parameters to obtain the most advantageous value of selected quality characteristic.

Monitored by the system of supervision and diagnostic objects belong both to the area of realized manufacturing processes, as also to machine tools and installations. So, in case of machining, the cutting process (tool and workpiece) is tracked, as in operation of devices and elements of machine tool. In both cases, there are used similar or even the same means.

The measuring activities associated with the monitoring and diagnostic can be realized both during the system operation, e.g. during machining, as well as after its end and also when the work is interrupted for e.g. exchanging the tool, or a workpiece. The system of monitoring and diagnostic fulfils the role of feedback between the working effects, condition of manufacturing means and manufacturing process and the program of system operation.

Sensors and inspection/measuring tools used by the monitoring and diagnostic system may be steadily jointed with the manufacturing equipment, or also may be inserted into the working area by means of robot arm.

The monitoring and diagnostic system may be divided into three main modules:

- Sensor's set
- Monitoring module
- Operation unit.

*The sensors* are the sources of signals enabling to obtain information about the system state. They should be situated possibly near the monitored object, should be distinguished by a great sensibility on the variations of the followed-up parameter and resistant to disturbances.

In *the monitoring module* there take place the evaluation of primary processed signals obtained from the measurement sensors and transferring the information to the machine tool control system.

*The operation unit* enables communication of the user with the monitoring system. Actually, it is still more integrated with the operation of machine tool control.

The realization of monitoring and diagnostics system tasks requires*:*

- Determining of factors and parameters, which values will be monitored,
- Choice and application of suitable sensors,
- Choice of suitable strategy.

## 10.1. FACTORS INFLUENCING THE REALIZATION OF MANUFACTURING SYSTEM FUNCTIONS

To select parameters, considered by the system of monitoring and diagnostic, one should analyze the factors, which may influence the realization of the manufacturing system functions including also the manufacturing quality, as one of the most important determinant of correctness of realization these functions. Fig.10.1 shows the grouping of these influences according to their sources. Disturbances of the manufacturing system working are derived from the errors, which may occur in all system components taking in consideration also the FMS staff. A man may cause, e.g. mistakes in setting the cutting parameters or tool paths, and make an error by loading the tool magazine. The main components of a manufacturing system are the following:

- Machine tool
- Systems supplying the machine tool in: energy, tools, parts, auxiliary materials
- Control system
- Surroundings.

The working machine tool creates a closed dynamic system, which includes its mass-elasticity-dissipation system, tool, machined part and the cutting process. In such a system, we have to do not only with static, dynamic and thermal distortions, which can disturb correct function of the manufacturing system, but also with the problem of its stability. Instability leads to self-excited vibration (chatter). The counteraction to it requires specific action strategies. Their application must be preceded by the vibration identification.

The significance of errors introduced by the systems of tools and parts delivery increases with the range widening of unattended manufacturing system operation.

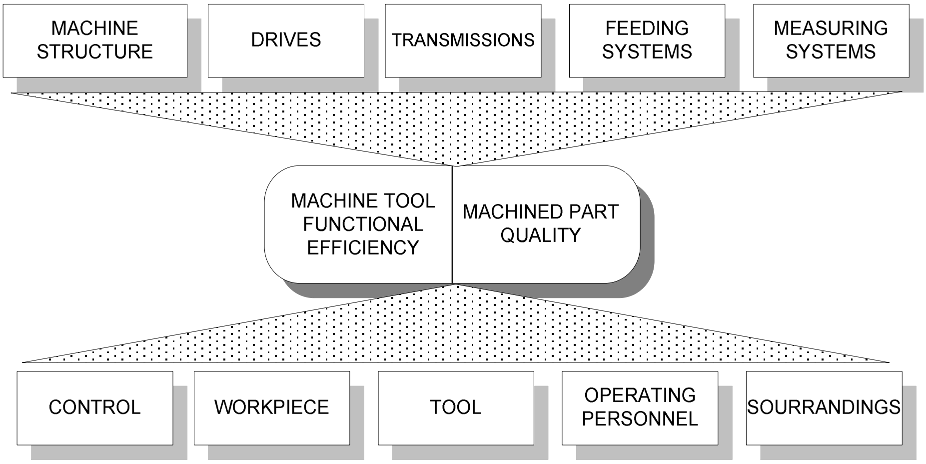



Fig. 10.1. Groups of factors influencing the manufacturing system functions

The disturbances which can be introduced by the control system may be of different matter associated both with the making errors by assembling the electronic systems, errors of functioning the systems components (e.g. reading device), as well as with errors of information system structure. The sources of disturbances also exist in the surroundings through e.g. temperature changes, interaction of electromagnetic fields, transfer of vibration through the foundation.

## 10.2. SENSORS USED IN THE MONITORING AND DIAGNOSTIC SYSTEM

By the monitoring of manufacturing systems operation, there may be used many different physical quantities characterized different processes, phenomena and parameters, which influence the automated manufacturing process. Adequately to these quantities there are used many different sensors. The variety of sensors, which can be used, are shown in the Fig. 10.2.

Under the notion of sensor, there is understood *a technical appliance acquiring physical and chemical states and also their temporal, or space changes, and converting them into signals (mostly electrical) suitable to processing* [1].

These signals are processed, first primary (usually in preamplifier), and then finally, depending on purpose to which the use of sensor is aimed.

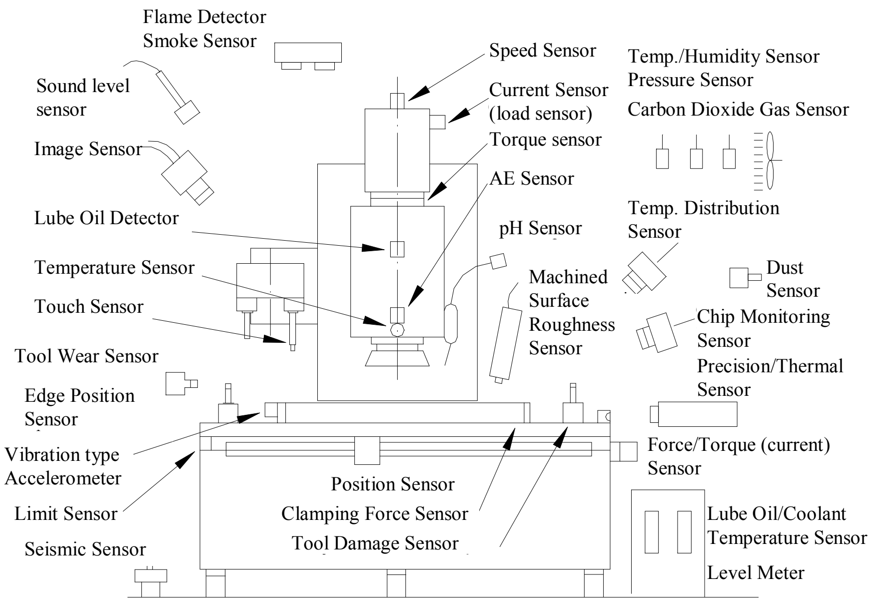



Fig. 10.2. Abundance of sensors for manufacturing system monitoring, after T.Morivaki [4]

Miniaturization of electronic systems allows in many cases to integrate in one encapsulation several functions. Actually, there can be distinguished sensors of three integration levels (Fig. 10.3):

1. *Base sensor* - contains only converter reacting on the measured quantity and converting it in electric signal

2. *Integrated sensor* - it realizes the functions of both the converter, as well as primary signal processing (preamplifier)

3. *Intelligent sensor* - an integrated sensor equipped with a system processing the signal and converting it in information suitable to the role which it plays in the system.

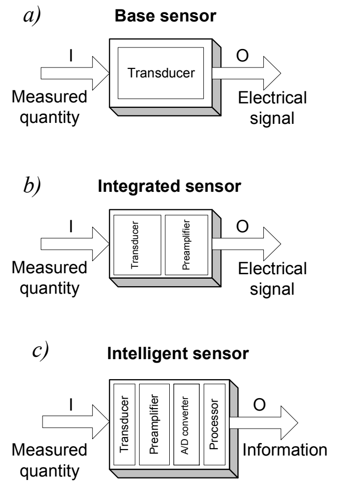



Fig. 10.3. Levels of sensor integration

Information on output of intelligent sensor is resulting of complex processing data. Under the notion of intelligent sensor is comprehend both, contained in one encapsulation an assembly: converter, preamplifier, and processor, or like more often appearing system: integrated sensor and connected with him, by means of signal cable, unit processing the data, which in turn can be integrated with control e.g. of machine tool or robot. The results of measurement can then directly interact on the control process.

The complex signal processing in an intelligent sensor (or in sensor system: converter, preamplifier, processor), covers the realization of functions, which can be expressed in three groups [1]:

1 – Static correction, such as:

- Linearization and characteristics shift,
- Scaling,
- Elimination of systematic errors (e.g. temperature dependent),
- Statistical processing,
- Approximation by given function.

2 – Dynamic correction, e.g.:

- Taking in consideration system transmittance,
- Comparison with introduced model.

3 – Evaluation of complex quantities, such as:

- Surface master (image identification),
- Frequency spectrum (identification of tool breakage, or wear),
- Status of sensor (self-monitoring).

The used sensors may be based on different principles of operation and utilize different effects whereas an electric signal on the exit may be obtained in the following ways:

- In a *passive* way, through the changing of one quantity which characterizes the outside supplying electric circuit, such as: Ohmic resistance, capacitance, inductance, resonance frequency,
- In a *active* way, through generating of voltage proportional to changes of measured quantity.

## 10.3. MONITORING STRATEGY

Drawing a conclusion about the system state, based on evaluated values of signal measures requires using of definite monitoring strategy. The following strategies belong to the most often applied:

- One-limit value
- Multi–limits values
- Master (running limit)
- Variable master (self teaching)
- Multi-parametric evaluation.

The simplest is the *strategy of one-limit value*. It consists in comparison of value of signal measure with the evaluated, most often empirical, the limit value. The exceeding there of upwards (or in certain cases downwards), means disturbance of monitored process course, or damage of some element of the machine tool and initiates the appropriate system reaction.

The *strategy of multi-limits values* are more often used and allows taking in consideration different cases which may take place during the process realization. Fig.10.4 show four-limits values of the cutting force, which may be significant for the tool condition monitoring.

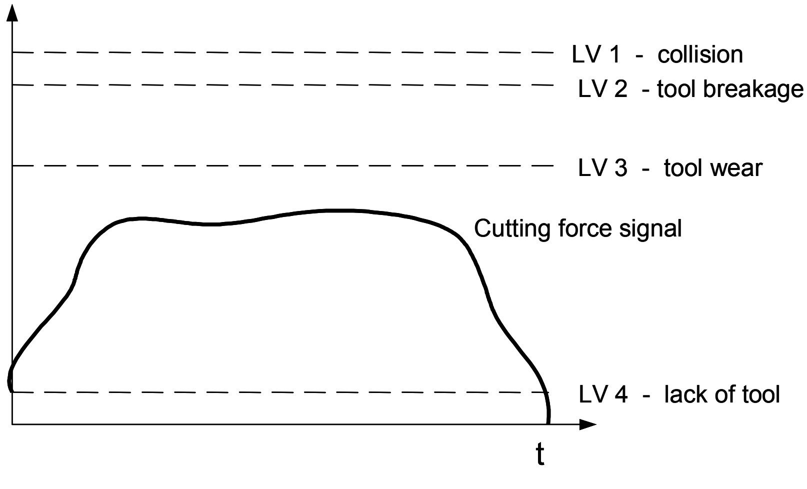



Fig. 10.4. Tool condition monitoring with four-limits of cutting force value

## 10.4. EXAMPLES OF TASKS OF MONITORING AND DIAGNOSTIC SYSTEM

The unattended operation of manufacturing system requires the monitoring of all its functional subsystems.

However, the most attention is devoted to the system functions and components associated directly with the realization of basic transformation in the system that is with conversion of the blank into the final product. In the manufacturing systems based on metal cutting machine tools, it means the necessity to supervise first of all the following:

- Condition of cutting tool,
- Working of machine tool,
- Part machining process,
- Workpiece.

If the diagnostic takes place during the process realization (e.g. the evaluation of tool condition during machining) it is called *on-line diagnostic*, otherwise - *off-line diagnostic*.

## 10.4.1. TOOL CONDITION MONITORING

Automatic monitoring and diagnostics of *cutting tool condition* belong to the most important tasks of the whole FMS monitoring system. This is associated with the fact, that, the tool is the weakest and fastest wearing element of this system. There are recognized two ranges of tool condition monitoring:

- Detecting the *unpredicted catastrophic tool failure* – that is statement that tool is no more suitable to further use,
- Following up the *normal tool wear* enabling evaluation how large is the remaining tool life available to further use.

Due to great importance of tool condition monitoring owing to undisturbed operation of manufacturing system, this problem is since a long time subject of attention (since the works of F.W.Taylor -1907). This problem gained in importance with the development of manufacturing automation. The effects of carried out through decades investigations resulted in the existence of many methods based on the use of different phenomena. The majority of these methods, due to the costs, or technical difficulties does not find industrial application and therefore will not in this place further discussed. All identification methods of the cutting tool condition can be divided onto:

- Direct and
- Indirect.

The *direct* methods are based on the measurement, either directly geometric features of cutter (its edges and surfaces), or the quantities directly depending on their changes. In the *indirect* methods however, there are measured quantities, which characterize other phenomena, which are influenced by the cutting edge wear. They are then based on the measurement of this wear results. The first ones better reflect the real state, but are often difficult in realization. However, the indirect methods are usually technical simpler, but their results are burdened with uncertainty associated with appearing measuring disturbances evoked by the influences of other factors onto the level of measured signal.

The most known indirect methods are the following:

1. Measurement of cutting temperature and thermoelectric power
2. Measurement of roughness changes, or workpiece dimensions
3. Measurement of vibrations and noise
4. Measurement of cutting force and derivatives quantities
5. Measurement of power consumption or motor power
6. Measurement of acoustic emission
7. Measurement of tool working time.

Despite significant number and variety of sensor tool monitoring systems, relatively small number (as reports W.Adam [1] about 10%) of machine tools is with them provided. The most significant reasons of this matter are the following:

- Not sufficient reliability of functioning of these systems, what creates the danger of appearing false alerts and useless disturbances in the manufacturing system operation
- Non-compatibility of sensor systems with construction of machine tools and their control systems occurring due to lack of standardized interfaces.

### 10.4.2. WORKPIECE MONITORING

The guaranteed by the manufacturer product quality belongs to most important criterions of market competition. It has since direct relation to its durability, functioning and utilization reliability. By comparable technical characteristic and cost, quality is the deciding factor taking in consideration by customer. However, quality is resulting from many factors, the accuracy of machining and their repeatability; belong to most important assumptions of each strategy in this area.

In case of flexible automated manufacturing systems, we have to do with high repeatability of the manufacturing process with minimal participation of human factor. The measurements of machined parts are usually carried out in random sampling [23]. They may be made either *in the working area of the machine tool*, or beyond the machine on the *special stations* provided with automated measurement equipment. The principle of measurements consists in estimation, in a defined coordinate system, position of any point on the plane, or in the space. On the basis of measurements of many points coordinates, there can be calculated any linear and angular dimension on the workpiece.

### 10.4.2.1. MEASUREMENTS IN THE WORKING SPACE OF MACHINE TOOL

The measurements in the working space of machine tool are made with the use of measurement *probes*. Following the introduction of them to industrial practice by the firm Renishaw in the year 1974, they became a standard equipment of centers and flexible manufacturing cells. Besides of checking the workpiece dimensions, probes my also fulfill other functions, such as e.g.:

- Inspection of tool condition,
- Part identification,
- Inspection of part setting in order to correct errors of fixing its on the palette and palette clamping on the table,
- Correction of position errors of rotating table.

The probe consists of measurement head and a shank, enabling fixing them on the machine tool for the measurement. Actually, there are in use many types of probes. They may be in general divided on *contact* and *contactless* probes. In the case of contact probes, the measurement point is located by contact of gauge plunger with the measured object surface. The contactless probes however have the optic measurement heads based on the numerical image analysis or on the using of the laser beam.

The contact probes are in turn divided into *impulse* (also called *switch-over*), which generate by the contact a signal causing the reading from the measurement systems of the machine tool NC axes, the values of coordinates of this point and *measuring* are provided with measuring transducer (Fig.10.5). In the probe head, there are embedded inductive transducers, which allow estimating the gauging point displacements in three axes. Indications of these transducers are added to indications of machine tool NC axes measuring systems.

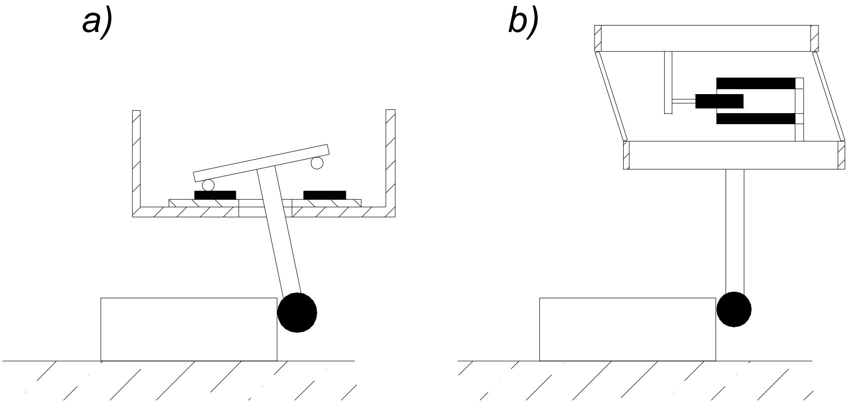



Fig. 10.5. Two types of probes: *a)* impulse, *b)* measuring

Most often are used the *impulse contact probes*. At the market, many producers offer such probes. Constructions of their heads may be based on different function principles. Depending on it, we can distinguish probes with:

- Electro-contact transducer,
- Piezoelectric transducer.
- Photoelement.

Function principle of the *electro-contact* probe consists in them, that a moving object, running into the probe gauging point, sticks it out opening one of the three series connected contacts. After breaking electric circuit on the transducer output appears a signal, which initiates reading of measured points coordinates and stoppage of NC axes driving. This type of probes characterizes signal scatter band from 0,35 to 1,0 μm. Improved construction of the electro-contact probe is a probe with auxiliary piezoelectric transducers arranged like electro-contacts circumferential at $120^o$ (Fig. 10.6). If the measure pressure exceeds 0,01 N caused deformation of one of the piezoelements generates voltage impulse releasing reading of the point coordinates. These coordinates are stored. Further displacement of object relative to the probe causes increase of pressure up to several hundredths of newtons and opening of one of contacts, what generates the second signal, so called *confirming*. This signal initiates stoppage of NC axes drive.

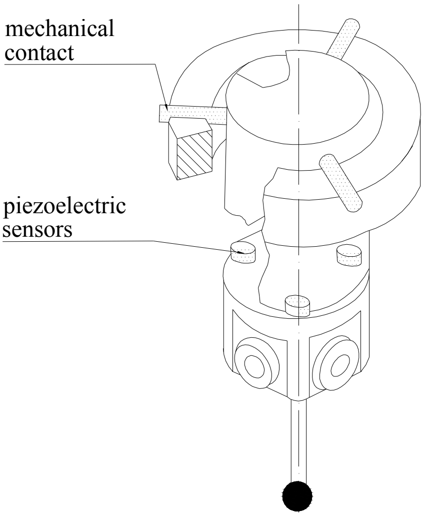



Fig. 10.6. Configuration of sensors in piezoelectric probe

Significant advantages bring the use of a probe to check the cutting tool condition. Thanks to the possibility of estimation the real tool dimension and position, there can be eliminated the necessity of its presetting in tool room, and it is possible to compensate the tool wear by changing the tool path parameter.

### 10.4.2.2. COORDINATE MEASURING MACHINES

The measuring probes are used to carry out relatively simple measurements. The complex and time-consuming measurements are realized outside of the machine tool, on special measuring stations. There can be used different automated measuring equipments on these stations, both, the universal as well as the special ones. The special equipment are adapted to a defined part spectrum. Their use is justified in case of stabilized production, when for a longer period changes in the structure of this spectrum are not anticipated. In the manufacturing system of great versatility and changeability of measuring tasks, there are used computer controlled coordinate measuring machines – CMMs (Fig.10.7).

The kinematical system of measuring machine consists of three mutually perpendicular NC axes creating the coordinate system x, y, z. It is then analogical to kinematical system of a milling machine with the difference, that in place of tool, there is installed the measuring head. The construction of measuring machines may be of different type. Their basic types are the following:

- Bridge-type,
- Outrigger,
- Column,
- Crossbar.

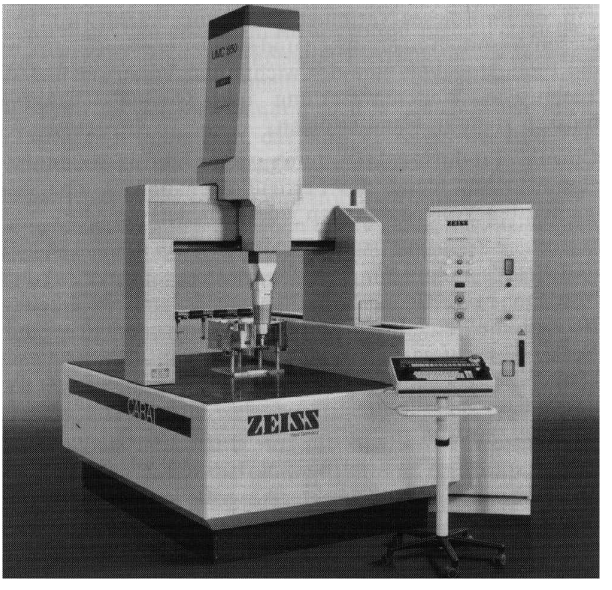



Fig.10.7. Bridge-type vertical coordinate measuring machine

In case of appearing strong air contamination, or marked gradients of environment temperature, the CMMs are located in a special cabin.

Compared to other means of measuring, the CMMs are characterized by many advantages, such as high accuracy, universality, flexibility, effectiveness, possibility of fast processing and evaluation (from different points of view) of measurement results, and ease to obtain broad measuring documentation. Though the CMMs may be used as unmanned working, autonomous stations, there is a tendency to integrate them together with another equipment in flexible manufacturing system.

# 11. AVAILABILITY OF FLEXIBLE MANUFACTURING SYSTEMS

Installation of flexible manufacturing system is associated with a high investment outlay. To avoid losses, the user of the system must pursue the highest its utilization rate. In this connection, both in planning the system, as well as during the operation such problems as: ability to work (disposability), failure risk, occurring frequency of possible disturbances and caused standstills, must be taken in consideration. The risk of failure is growing with the complexity of the system. In case of multi-machine, flexible manufacturing system, the risk is therefore higher than in case of single machine tool. It is but inversely with the ability to work, especially when the system includes replaceable machine tools; the failure of one of machine tools does not cause the breakdown of the whole system operation. The possibility of occurring disturbances in working of manufacturing system depends on its complexity, but besides also on technical solutions applied to functional subsystems, such as: the tooling and workpiece subsystems, chip disposal, feeding with technological fluids, and also of monitoring and diagnostic system. The utilization rate of the system depends also on human resources, production organization and of surroundings conditions. Its raising requires then complex activities, covering both the phase of planning and implementation, as well as using of FMS.

In order to describe the ability to work of the system and its effectiveness, the notions *technical availability* – $D_t$, and the *real utilization* - $W_r$ [11] have been introduced. The notion of technical availability comprehends the relation of difference of working time potential of machine tool and standstills time generated by technical causes, to the potential of working time. The technical causes are then divided on *direct*, associated with failures of functional devices of the machine tools, and *indirect* associated with failures of other components of manufacturing system. For a defined work cycle, e.g. whole day (three shifts) of one machine tool (machining centre), the technical availability is expressed by the formula:

$$D_{tc} = \frac{T_{cc} - T_{ptc} - T_{psc}}{T_{cc}} \tag{11.1}$$

Where

$D_{tc}$ – technical availability of one machining centre

$T_{cc}$ – working time potential of centre

$T_{ptc}$ – standstill times generated by direct technical causes

$T_{psc}$ – standstill times generated by indirect (system) technical causes.

The technical availability of the entire manufacturing system is equal to:

$$D_{is} = \frac{\sum_{i=1}^{n} \left(T_{cci} - T_{ptci} - T_{psci}\right)}{\sum_{i=1}^{n} T_{cci}} \tag{11.2.}$$

Where

$D_{is}$ – technical availability of manufacturing system

$i$ – running index of machine tool included in the system

$n$ – number of machine tools in the system

In the industrial practice, the real use of flexible manufacturing system is smaller than its technical availability. It is caused by this, that besides of standstills generated by the technical causes, there appear yet such ones, which may have organizational character. To them, belong standstills caused by:

- Lack of tools,
- Lack of material or semis,
- Maintenance,
- Ordering works,
- Elimination of operator errors,
- Carrying out of correction and optimization of the part programs for machine tools and other NC equipment.

The real utilization of one manufacturing centre may then be estimated from the equation:

$$W_{rc} = \frac{T_{cc} - T_{ptc} - T_{psc} - T_{poc}}{T_{cc}} = D_{tc} - \frac{T_{poc}}{T_{cc}} \tag{11.3}$$

where:

$W_{rc}$ – real utilization of one machining centre

$T_{poc}$ – standstills time generated by organization causes, other symbols as in formula. (11.1)

For the entire flexible manufacturing system, it will be according to equation:

$$W_{rs} = \frac{\sum_{i=1}^{n}\left(T_{cci} - T_{ptci} - T_{psci} - T_{poci}\right)}{\sum_{i=1}^{n} T_{cci}} = D_{is} - \sum_{i=1}^{n}\frac{T_{poci}}{T_{cci}} \qquad (11.4)$$

Where:
$W_{rs}$ – the real use of flexible manufacturing system
$D_{is}$ – technical availability of manufacturing system
other symbols, as in formula (11.3), whereas: $i$ – running index of machine tool included into the system.

Balance of working time being in disposition of the user of flexible manufacturing system, may be then presented, as on Fig.11.1 using the Sankey's diagram.

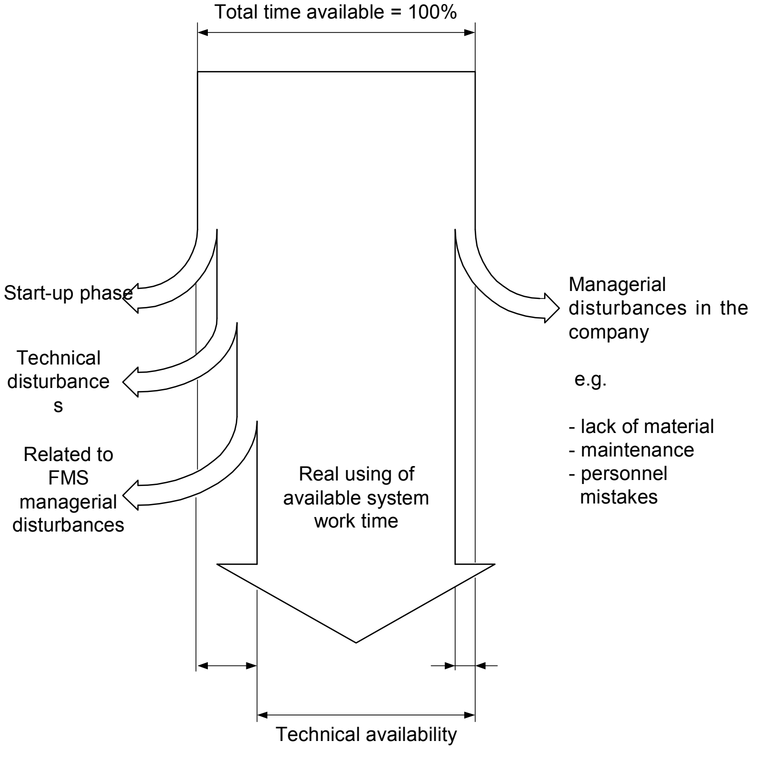



Fig. 11.1. Sankey diagram of FMS available total time using

The responsibility for standstills caused by disturbances of technical nature bears the supplier (producer) of system and its components, whereas standstills caused by organizational reasons, its user.

Forschungsinstitut fur Rationalisierung in Aachen (Germany) carried out investigation of work effectiveness of flexible manufacturing system (FFS 630-4 of Werner) which consisted of four machining centers and was installed in a middle sized enterprise manufacturing pumps (cit. after [11]). Measurements of utilization of the working time in three-shifts work, during 20 working days. The results obtained are presented on Fig. 11.2 [11].

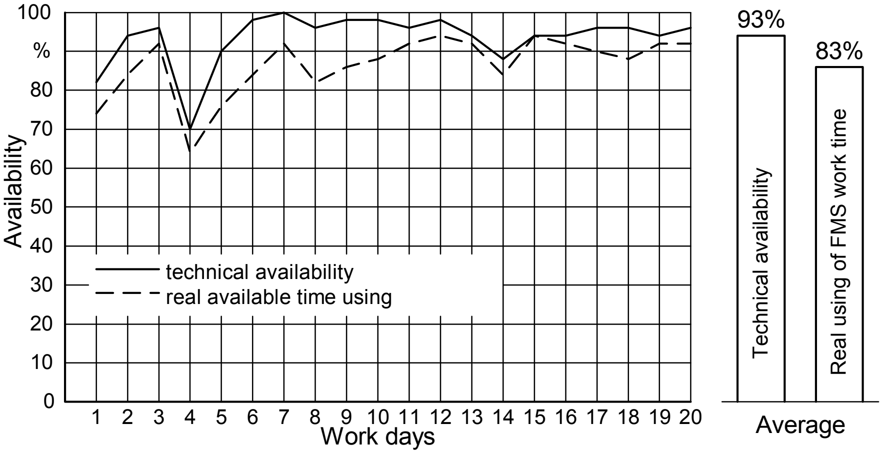



Fig. 11.2. Example of diagram presenting the technical availability and real FMS work time using ([11])

Significant are the low values of system technical availability at the beginning of the investigated period. In these days have occurred disturbances in operation of larry car transport of pallets and in automatic tool changing control. In average, for the whole period of twenty days, the technical availability amounted to 93%, whereas the real use of system was 83%. In case of appearing disturbances in operation of the flexible manufacturing system, important is quick identification of the real causes and elimination thereof. In a complex system, not always it is easy, taking in consideration the number of possible sources of disturbances. Fig.11.3 shows an example of division of the breaks in FMS operation reasons onto groups, both technical as well as organizational character.

The prime reason of organizationally caused disturbances in working of flexible manufacturing system, especially in the first use phase is, as usually, not sufficient accommodation of organizational enterprise structure, created in the past, to the requirements, which presents the automated production system.

In comparison to stand-alone NC machine tool, or machining centre, the flexible manufacturing system is characterized with markedly higher utilization rate (Fig.11.4). Some factors are involved here; decreasing, thanks to central control, of downtimes caused by organizational reasons, decreasing, thanks to automation, of times used for changing tools and parts, and the possibility of unattended operation on the third shift.

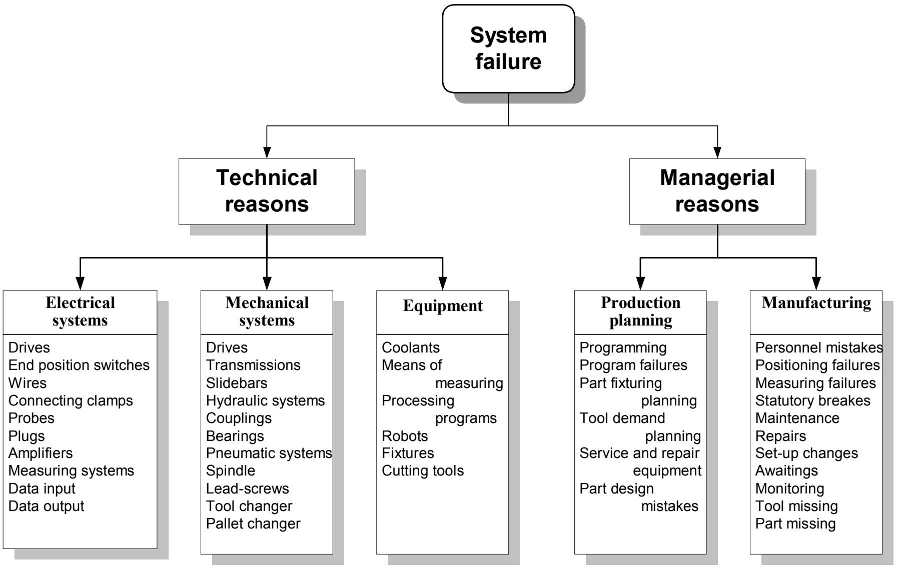



Fig. 11.3. Classification of reasons of disturbances by the FMS operation

Besides of direct influences on work effectiveness, and also on manufacturing costs, the using of flexible manufacturing system, contributes also indirectly to the reduction of this costs. This is achieved first of all by decreasing the production in process and reducing inventory, and also by minimization of outlays on planning and production control.

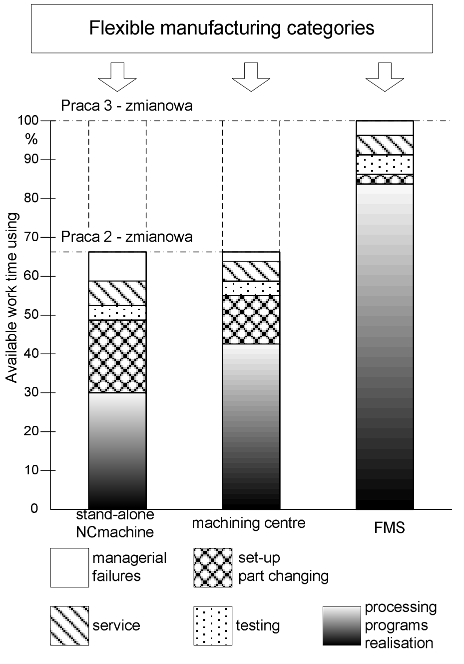



Fig. 11.4. Available work time using by different flexible manufacturing categories

Flexible manufacturing systems are regarded as one of the most efficient methods to employ in reducing or eliminating problems in the manufacturing industries. Achievement of FMS benefits depends decisively on correctness of decisions made by the system planning. The planning process should begin with the answer to following questions:

- What are the real manufacturing targets the company should be aiming for by purchasing an FMS?
- How will be determined the economical efficiency of system in use?
- Where is the achievement of main savings expected?
- Which compromises are acceptable?
- Is the limit of investment costs determined and is it to all project team members known?
- Where the allowed saving possibilities in case of investment costs are limit exceeding?
- Are the costs of staff training and FMS maintenance taken into account?

Next, there should be formulated, with reference to all functional areas, possibly detailed lists of requirements and expectations to be fulfilled by the system. On the base of them, there should be in turn specified problems, which must be discussed with the suppliers. Fig.11.5 shows the most important groups of problems, which should be considered by the planning of a FMS.

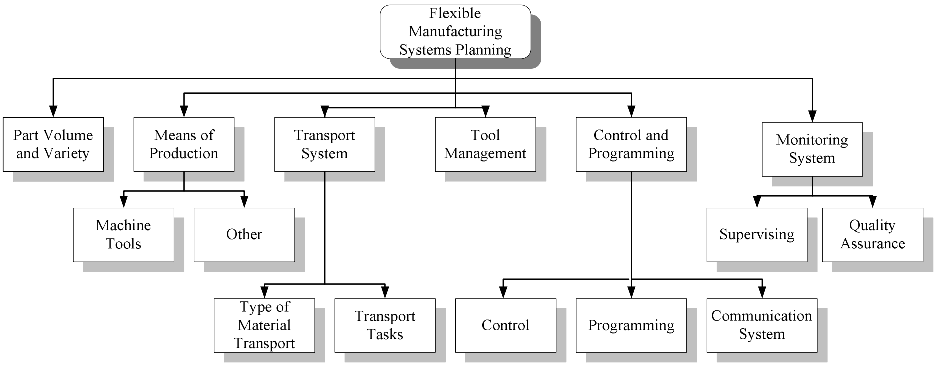



Fig. 11.5. The main problem areas to take in consideration by process of FMS planning

For each group of problems mentioned on Fig.11.5 there can be formulated many detailed questions. E.g. with reference to the tool management system there should be determined:

- Which type of tools, divided into standard and special once will be used in the system?
- What will be the general number of tools, which should be stored in the central tool storage of the system?
- Where will be situated central tool store of the system?
- What will be the distance between the central tool store and the machine tools?
- How will be realized transport of tools between the store and machine tools, and between the machine tools?
- How will be realized the tool measurement and preset, and which equipment will be to this end suitable?
- How will be transferred the tooling data to the CNC unit of machine tools?
- How the monitoring of tools will be realized on the workstations?
- Which method of tool automatic identification will be used?
- How the sharpening of tools and exchanging of the inserts, will be organized?
- How the exchanging of tools in integrated magazine (manual or automatic) will be realized?

A set of questions which should be taken into account in a given case, depends not only on technical factors, but also on such problems as: manufacturing program of enterprise, actual state of technology in particular functional areas of FMS, anticipated changes of manufacturing program and production volume, or also the actual condition and accepted concept of development of production automation in the enterprise.

By planning the implementation of flexible manufacturing system, the enterprise often meets dilemma of the necessity to realize inverse aims (Fig.11.6, according to [52]). And so, e.g. the increase of flexibility brings decrease of productivity, whereas the increase of complexity of manufacturing, means higher complexity of manufacturing system, and through this, decrease of its reliability and availability.

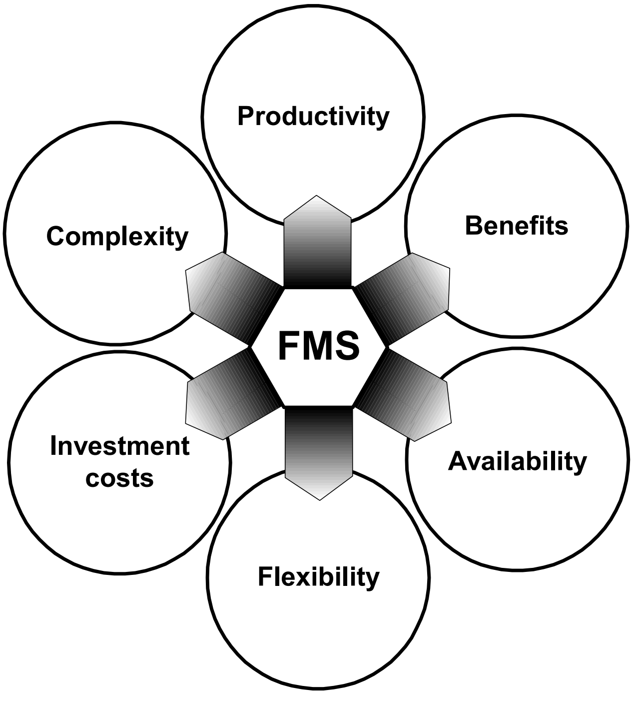



Fig. 11.6. Dilemmas of flexible manufacturing automation

To achieve the decrease of investment risk there is the necessity to balance thoroughly the proportion between inverse factors.

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