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Wrocław University of Technology

Production Management

Jacek Czajka, Kamil Krot, Michał Kuliberda

SELECTED ISSUES OF PRODUCTION SYSTEMS ORGANISATION AND COMPUTER AIDED PROCESS PLANNING

Production System Organisation

Wrocław 2011

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1 Introduction

Contemporary requirements, with which production companies are presented, are coercing production in ever-shorter time and at ever-smaller expense. In order to meet those expectations companies are undertaking various actions: they improve work organisation, improve employees' qualifications, improve product quality simultaneously minimising the amount of defects. One of key areas within an enterprise, requiring implementation of improvements, is broadly defined manufacturing. For many years companies have been striving to accelerate realisation of an entire production process by introducing new solutions to the area of manufacturing. Those actions comprise i.a. modernisation of machinery, what allows products to be manufactured faster, of better quality, and often at smaller cost of production. Apart from or in tandem with production resources in form of machines, acceleration of manufacturing processes is achieved by work organisation improvement.

In hereof paper are presented issues related to designing manufacturing systems taking into account planning of workplaces allocation (layout). The fundamental task in this area is selection or modification of equipment in form of workplaces and means of transport. It is indispensible during that process to take into consideration employed technologies and appropriate utilisation of surface designated to realise manufacturing processes.

In chapter 3 are presented types of organisations of production process considering relations between workplaces.

In chapter 4 is presented the concept of Group Technology. Its features were reviewed and its usefulness in technological process designing and production process designing was shown.

Chapter 5 contains description of procedure for dealing with design of workplace allocation. That and following chapters reviewed how those works can be aided through application of information tools. Tools for production systems designing were characterised as well as tools for simulating its operation.

The second part of this paper contains information on the subject of computer aided technological processes designing with computer tools applied – systems aiding technological processes planning – CAPP (*Computer Aided Process Planning*). The emphasis needs to be put on the course of manufacturing process as the very base for production system designing. That is because the course of a manufacturing process determines transportation routes in accordance with an established list of technological operations and assigned to them workplaces.

2 Production organisation – machines allocation

Investment outlays connected with development of modern production systems are very high, hence a diverse range of analyses and simulations are used beforehand of implementation of solutions regarding organisation of a production system. Those costs can be lowered through an appropriate choice of the type and number of production devices and their optimum allocation within a machine shop. That decision process in practice take involves variant, on numerous occasions repeated solution of issues of the same kind, until satisfactory results are reached fulfilling predetermined assumptions. Correct conducting of that process has got also a significant influence on:

- maintenance costs cutting of production system,
- improvement of machine utilisation rate,
- increase in system efficiency being the result of better machines allocation and higher transport throughput [1].

Optimisation of machines arrangement belongs to one of the very first tasks, which should be solved in the preliminary phase of designing a system. Characteristic for contemporary production systems low level of inter-operational stocks compels very strict, mutual relations between machines.

Allocation of production objects is expressed in mutual arrangement and determination of positioning relative to successive components of a production process [2]:

- machines and devices,

- workplaces,
- workcells,
- departments,
- factory halls and buildings and transport chains.

Numerousness of appraisal criteria for LAYOUT plans renders impossible to determine and optimum arrangement.

Workplace allocation analysis is conducted when:

- there are changes introduced into the product i.e. e.g.: by improving effectiveness of existing production or, when a new product is added to the assortment of already manufactured ones,
- production management techniques are being introduced, such as e.g.: *Just-In-Time* or *Group Technology*,
- allocation of workcells, production lines, departments as well as entire factories is being planned or improved,
- subject to improvement is flow of materials in production process, flow of parts, groups of parts, products,
- new equipment, means of transport are ushered in,
- the way of storing is being planned or changed,
- there is a need of presentation and comparison of different allocation alternatives simultaneously in text form (reports) and graphical.

Problems of designing workcell allocation in manufacturing systems constitute examples of tasks with multiple solution variants. If there are *"N"* workplaces to be allocated in *"N"* spots, then we get *"N!"* of possible configurations [3], [2]. If the number of workplaces and possible spaces of their localisation are not equal – *"n"* and *"m"* correspondingly, where $n<m$

then the number of possible combinations is determined by expression: m!/(m-n)!. It is less than n!, however it is a lot still. [3], [4].

Problems encountered in practice are far more complicated, because they take into account additional conditions and constraints resulting from technology, construction and equipment of a building (e.g. common power supplies, special foundation, restricted bearing capacity of ceilings), health and safety conditions (e.g. required distances between workplaces) and others. Such high number of factors influencing the way of arranging workcells renders the problem difficult to solve. Coming useful here can be computer techniques, which allow for presentation of a problem in form of a model and subject it to different analyses. Computer system can give answer to the question: which workplaces allocation is optimum for assumed criteria?

Application of computer techniques in solving problems related to creation of allocation plans for workplaces holds the following advantages:

- completion of required computations and generation of several variants of solutions in substantially shorter timeframe compared to traditional techniques.
- solution of much more complex project tasks in terms of entered data,
- design process is independent of designer,
- use of a computer leads to obtainment of a solution based solely on mathematical considerations, which can subsequently be developed and changed in an objective manner,
- possibility of process optimisation,

- possibility of integration with CAD and ERP or PPC and SFC systems.

In practice, the problem of allocation plan creation is solved by means of a single or multiple presented below approaches [3], [5]:

- precise mathematical procedures,
- heuristic methods,
- probabilistic methods,
- graph theory.

The goal of those procedures' functioning depends on applied ways of expressing relations between allocated workplaces or objects. When relations are expressed by means of "qualitative coefficients", they are often presented by means of "links matrix" where the aim is maximisation of "closeness" between workplaces. On the other hand when relations between objects are expressed in "quantitative units" obtained from the matrix of graph of "FROM_TO", the aim is minimisation of costs related to transport of materials, being the result of decreasing distances between departments, and connected to it flow of materials and unitary transportation costs. In many cases, especially when designing new facilities, material flow system remains unknown until workplace allocation plan is constructed. Cost of transport attributable to a unit of product in this case is accepted (assumed) with a high approximation, outcome of that action being minimisation of costs which a product of costs corresponding to flow of materials and distances. Thus those costs are assumed (with a certain approximation) to be costs of material transportation. Procedures allowing for obtainment of solution for all methods presented above are independent both of the way data was prepared and the method of solution optimisation. Construction of solution procedures, used during LAYOUT plans creation for the first time, (exclusive of method of optimisation) is based on three fundamental steps [3]:

- first step: choice of criteria for selecting workplaces, which will be considered as workplaces to be arranged according to layout determined on basis of relations between objects,
- second step: distribution of every object to an appropriate place is done in order to attain a particular aim (minimisation or maximisation of certain function),
- third step: this step takes place in order to graphically develop the workplace allocation.

Optimisation procedures of constructed earlier workplace allocation are considerably diverse between each other due to applied rules of choosing workplaces in successive steps. Solution acquired on the basis of optimisation procedures constitutes always one of possible solutions. It is the result of overlap between effects obtained in "three steps" described above.

Below are listed exemplary optimisation procedures of workplace allocation:

- Gavett-Plyter branch and bound method from the group of exact science methods,
- Hillier-Connors method (HC 66) being a simplified version of branch and bound method,
- MAT method (*Modular Allocation Technique*) representing the group of heuristic methods,
- Schmidgall's triangles method,
- CORELAP method, using matrixes of functional relations,

- CRAFT method, from the group of so-called local optimisation methods,
- Bender Distribution algorithm, using methods of partially complete programming.

The choice of workplace allocation optimisation method can be made after explaining, whether:

- new cells are designed, or are existing cells being changed,
- there are restrictions regarding shape of the surface, across which workplaces are distributed,
- dimensions of allocated workplaces are varied,
- there are objects of constant localisation.

The basis for selecting a method are the following assumptions:

- when designing new workcells, a new allocation is built from scratch,
- when modernising existing workcells, an allocation of workplaces is known, which can be adopted as a preliminary arrangement.

In the first case the most appropriate are going to be step methods, which do not require knowledge of preliminary allocation, or combination methods, constituting the conjunction of step and iterative methods. Step methods are used then to generate preliminary allocations, which are subsequently improved with iterative methods.

When designing new workcells, task groups are separated, which are dependent on the degree of freedom in shaping surfaces, across which workplaces are distributed. Methods having a limited possibility of choosing a space, precisely determine the structure of workplace localisation spaces by the shape of surface. Methods with unlimited possibility of choosing spaces, do not determine the shape of the surface. It is obtained as a result, along with workplaces arrangement. When modernising existing workcells the shape of surface and structure of workplaces localisation is always a constraining factor.

3 Types of production process organisation

One of the most commonly used classification criteria for types of organisation of production is taking into account couplings between elements of a production system. The following types of production system are distinguished:

- linear form of organisation of production,
- cell form of organisation of production,
- technological form of organisation of production,
- form for items not subject to inter-operational transport,
- mixed solutions.

That classification comprises transport connections between elements of production system, as well as remaining in a strict relationship with it inter-operational storing.

3.1 Linear form of production process organisation

Linear form of production process organisation corresponds to subjective specialisation of production system, where there is similarity with reference to majority or all technological operations, and their order as well. In linear form of organisation of production connections between elements of a production system, plus the way they are allocated are compliant with the order of performing technological operations.

Example of such allocation of workplaces is shown in fig. 1. Flow of material is one-way and runs between consecutive workplaces. There are no recurrences. Beside workplaces small storages can create. It follows from different performance of workplaces and workers. This form of production organisation is most commonly encountered in enterprises producing a single or several products in large series (e.g. a factory assembling cars).

Benefits resulting from this form of organisation of production process are:

- shortening of inter-operational transport time,
- shortening of machining time,
- easy planning and control.

This form's disadvantage is lack of flexibility. LAYOUT plan is built with a particular product in mind. Costs of its modifications can be significant, hence is comes as no use for companies, which are changing often assortment of their products.

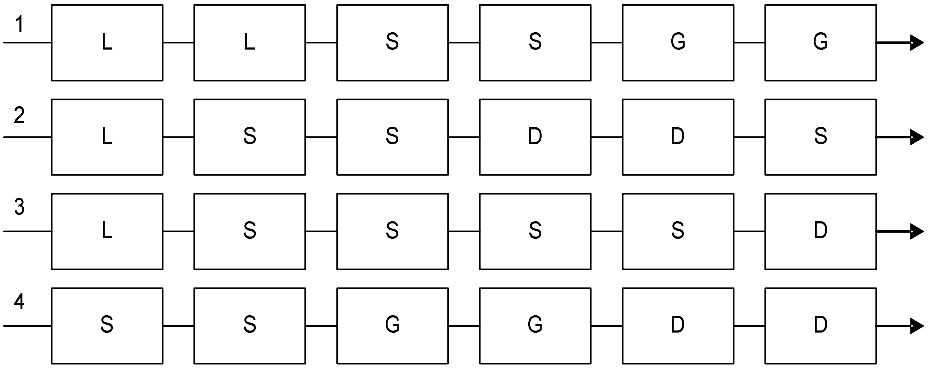

Fig. 1. Diagram of workplace allocation in production lines: L –lathes, S – shapers, D – drills, G – grinding machines

Production lines are a form of production organisation, which can be with little effort subjected to automation processes. Application of automatic transport and positioning and mounting, and also use of machine tools working in an automatic cycle is a characteristic trait of automated production lines.

Grouping workplaces into production lines demonstrates – in comparison to technological machine allocation, and also subjective in subjective cells – multiple benefits, which result mainly from higher constancy in sequence of performing technological operations and also from straightforward course of machining process. Length of transportation routes succumbs to significant shortening, especially after connecting workplaces with means of transport. Work efficiency increases due to possibility of applying highly specialised machines and devices. Control over production lines is easier to exercise and it's easier to prepare a production plan. Additionally the production floor is better utilised.

Drawback of the aforementioned allocation of workplaces is lack of full synchronisation of technological operations' times, what leads to incomplete utilisation of machines and devices. Admittedly it can be partially compensated through creation of semi-finished products storages, however it is possible only in narrow time intervals. Furthermore manufacturing in production lines is possible only, when production plan ensures relatively high constancy of technological operations performance sequence.

3.2 Cellular form of production process organisation

In the cellular structure items, being manufactured in a facility, are assigned to appropriate groups. Every group of items is manufactured in a separate workcell. A workcell can be entirely automated when large number of items of a particular product is required. In case of cellular production, costs of producing a certain product fall considerably. Those costs are split into fixed (costs related to workplace preparation) and variable (cost of labour, material). Cost of manufacturing a product is dependent on the number of produced items at the identical workcell configuration and the same setup of machine tools. The greater the production, the lower the cost per single product. Cells often adopt shape of the U letter – it facilitates walking for operating personnel from one machine to another. The entire technological process of an item is realised within a single cell. Example of such arrangement of workplaces in depicted in fig. 2.

In workcells having cellular form of production organisation the way of allocating workplaces is a many factors function, i.a. their material-energetic and functional relations, relations with the environment, shape of hall floor, way of assisting by auxiliary economies, restrictions in availability and other.

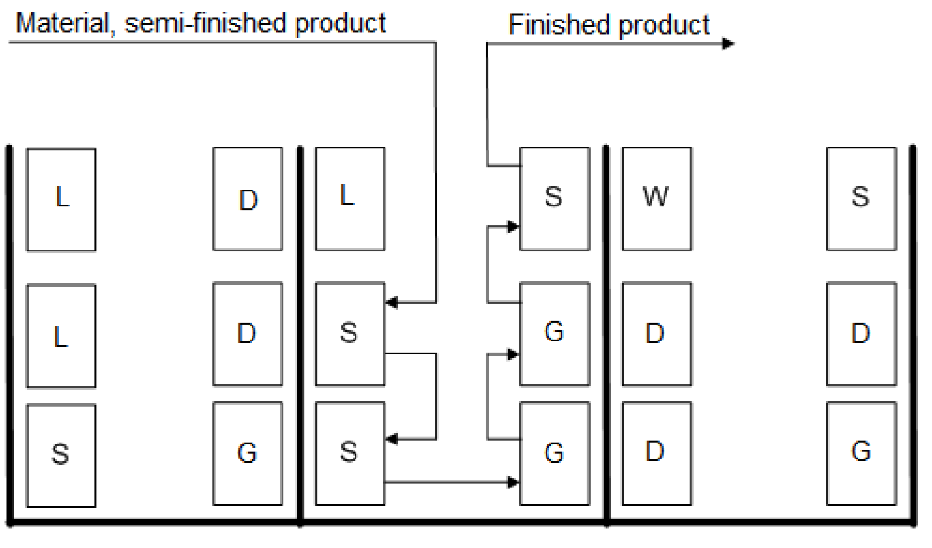

Fig. 2. Diagram of workplace allocation in item workcells with the course of technological process: L – lathes, S – shapers, D – drills, G – grinding machines

Determination of the way workplaces are arranged in cell structures requires usually the use of special models and methods (e.g. of optimisation)

3.3 Technological form of production process organisation

Technological form of organisation of production is characterised by the fact, that in the production system are performed sets of similar technological operations of different products. Assortment of manufactured products, is broad and is subjected to constant change. Lack of exact allocation of tasks to elements of the production system causes, that relations between them are impermanent and can take their course in different directions.

In that situation workplaces are grouped together, based on operations which are performed on them. Departments of lathes, milling machines etc are created. Technological form of process, offers flexibility, and employees gradually become experts in particular activities. Example of such allocation plan of workplaces is shown in fig. 3.

Drawbacks which result from using this form are:

- high costs of inter-operational transport,
- congestion being created during transport,
- complexity in planning and control,
- low efficiency,
- extension of production cycle.

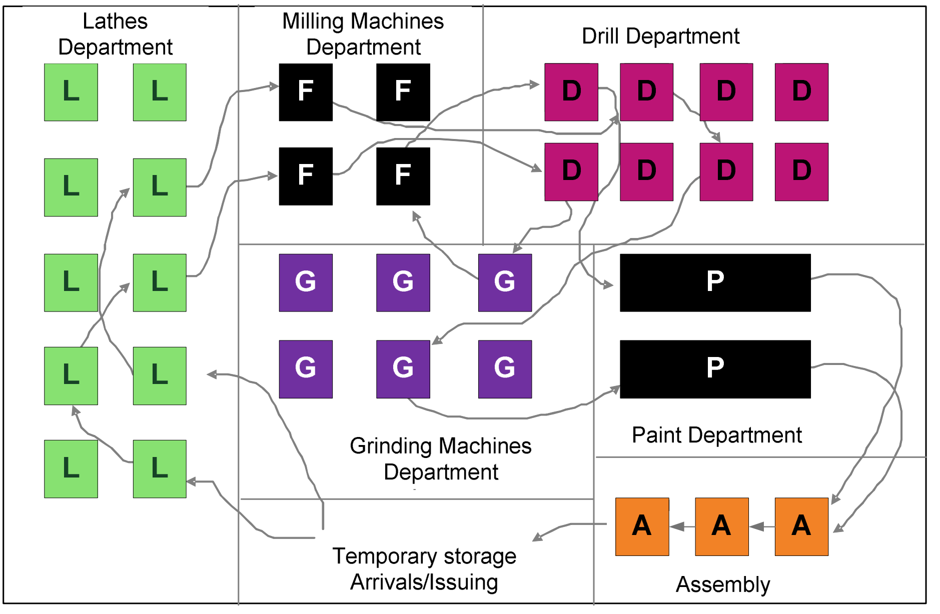

Fig. 3. Exemplary LAYOUT of technological organisation of production

Technological grouping of workplaces comes as a benefit during unitary production and low-volume production. In those technological conditions manufacturing system allows for better utilisation of machines and devices.

Technological form of production process organisation can be realised in a dual form:

- groups of technologically similar stations not creating separated workcells. Relations exist solely between groups of stations within a single cell. There is lack (in general) of relations between stations of the same type. Structures of workcells of that kind are called temporary technological structures, whilst cells are described as cells segmentwise technologically specialised.

- groups of stations technologically similar creating separated workcells. Each of cells realises only a certain part of product's technological process e.g. turning, drilling, grinding. In this case there are relations between workcells, however there is lack (in general) of relations between stations within a single cell.

3.4 Layout for immobile items

That form of production system organisation is used when product does not move from place to place – its immobile (fig. 4.). Being moved around is equipment required for manufacturing the product. Such solution is normally used for production of cumbersome or large items (shipbuilding, plane construction etc.), which cannot be in an easy manner or at all transported. Recently also companies manufacturing cars of high-end class have been using this solution.

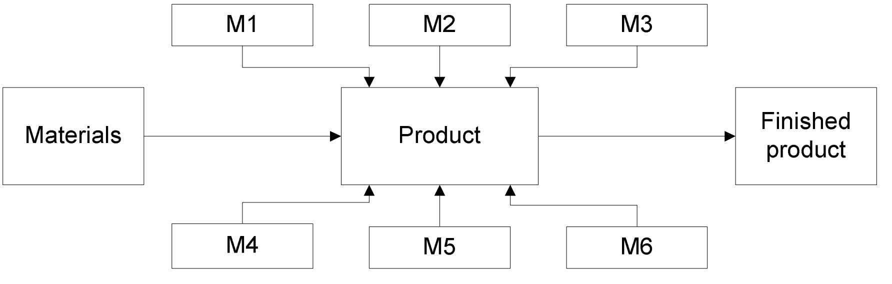

Fig. 4. Exemplary Layout plan for "immobile" items

Benefits which result from application of that form of organisation of production process are:

- low costs connected with transport of cumbersome products,
- lower risk of damaging them,

Such form of production organisation causes however increase of costs related to moving equipment.

3.5 Mixed forms

Not all companies are capable of adopting only one type of a LAYOUT plan. Along with enterprise's development grows the diversity and quantity of manufactured products. Example of mixed plan of production organisation is shown in fig. 5.

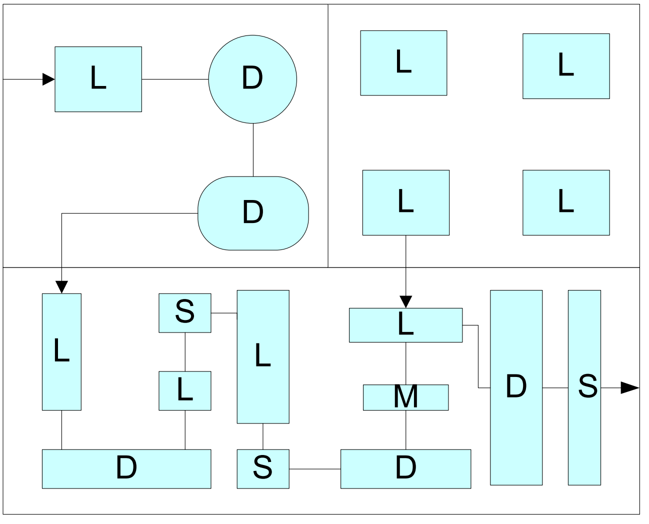

Fig. 5. Mixed form of organisation of production

Unfortunately none of presented above types of LAYOUT plans is completely capable of satisfying company's demands. In that case mixed forms are being used. There are products, for which cell LAYOUT is used, for others linear.

4 Group Technology

Group Technology is such a philosophy of management, which is aimed at grouping products of similar pattern or of similar technological process [3], [6], [7], [8], [9]. Manufacturing in workcells can be defined as application of group technology, where machines are grouped together depending on requirements set by technologies of items produced there. Main objective of applying Group Technology is simultaneous organisation of machines in workcells and parts technologically similar into groups in order to minimise the route, which is covered inside a workcell. Analysis of arrangement of machines inside a cell has to lead to reduction of costs related to transport of inner and intercellular material.

Amongst fundamental advantages of Group Technology one has to include [10], [11], [12], [13]:

- **decreasing of transport operations number–** instead of dividing available equipment into departments conducting one type of processing, it is possible to divide available departments in accordance with groups of parts being machined within them. Each of departments becomes an independent cell capable of performing all or majority of operations requisite, in a given product family. It results in parts being produced in shorter time and within one department and it is not necessary to transport machined parts between other cells. It simplifies flow of materials and products processed by the manufacturing system.

- **shortening of set-up times and decrease of costs related to tools necessary for machining** – due to machining of similar products being conducted, used tools are standard ones. It entails also reduction of the set-up time.

- **decreasing of all costs related to preparation of production** – if a need arises of designing and subsequently manufacturing new products, the product is placed in the group of parts technologically similar. At that point there is only necessity of modifying already existing production plans and instrumentation. It shortens the process of preparing production.
- decrease of inter-operational stock,
- increase of crew's satisfaction from the work performed,
- variable production plan,
- possibility of flexible utilisation of machine tools temporarily under lesser load,
- flexibility of technological routes,
- possibility of machined parts' recurrence,
- susceptibility to computer aided automation,
- integration at the stage of production preparation with processes of control, transport, storing.
- it constitutes basis for designing and maintaining computer aided manufacturing systems (FMS, CIM/CAM etc.).

Advantages of Group Technology are also visible in own-cost accounting and price formulation, internal and external settlements, service of spare parts. Under conditions of free-market economy the existence of production organisation without employing classification of parts and assemblies becomes impossible. Such approach induces application of an appropriate allocation of machines and devices at the production floor.

Group Technology requires a greater assortment and magnitude of production equipment. Each of machine tools of a production system with implemented Group Technology needs to be self-sufficient in terms of instrumentation, what frequently causes duplication of equipment. The quantity of equipment required when using Group Technology also increases.

The main difference between traditional setting of machine tools in a generic system and in a machining cell, is that machines are set up and grouped together. In generic setting of machine tools, machines are grouped according to the type of machine tools (i.e. separately lathes, milling machines, drills, grinding machines etc.)

A machining cell is constituted by a set of workplaces intended for manufacturing different parts of similar technological processes. The rule of organising a machining cell is to manufacture "ready-made" items, therefore in a cell apart from machine tools there are stations for induction hardening, stations for manual machining, control, and seldom at the beginning of a cell are placed forging presses, machines for centrifugal casting etc. [14].

In the processes of designing the organisational concept of production according to Group Technology helps to classify and code parts on the basis of their geometrical properties and other similarities. Group Technology is often used in the process of designing products, because a product is classified and coded there, allowing for utilisation of those codes by computer systems. Thanks to that, a technologist can find the appropriate database for an already existing product and can use it for designing a new part of similar utility and geometrical traits [3], [15], [4].

In the manufacturing process Group Technology focuses on grouping similar technological operations, similar tools and procedures of machine tooling, and also similar methods of transporting and storing. Produced parts, although can look differently, in reality are subject to the same production process. Application of Group Technology is based on idea of classifying manufactured parts into families. Thanks to identification and grouping of parts into families, simplification and standardisation of production processes of parts from the same family can be achieved.

4.1 Classification and coding of parts

Attribution to parts of similar properties appropriate symbols is coding, whilst identification of different classes, based on corresponding to each other properties of items is classifying – fig. 6.

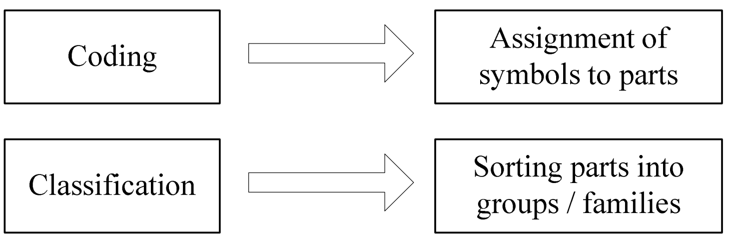

Fig.6. Coding and classification of parts

Similar parts can have the same code, an exemplary one is presented in table 1.

Table 1. Example of code

Position nr 1	Position nr 2	Position nr 3	Position nr 4	Position nr 5	Position nr 6	Position nr 7
1	3	2	8	8	5	3

In the process decoding, precise geometrical and other product features remain unknown, only their approximated values are known – fig. 7.

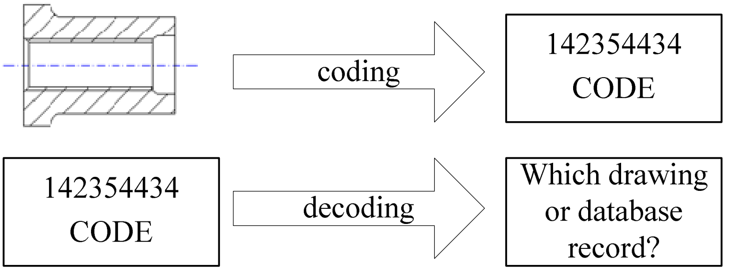

Fig. 7. Coding and decoding parts [15]

Coding uses the likes of numeric, alphabetic as well as alphanumeric symbols. Every code entry describes a property of the part described. Beforehand of coding a part, one has to know the structure of the coding system.

There are three fundamental types of codes in Group Technology:

- **coding according to item features** – the meaning of every position in the code is constant,
- **hierarchical coding** – the meaning of every position depends on the meaning of preceding position,
- **hybrid coding** – some are attributes of other positions, whilst other are based on the rules of the hierarchical code.

Group Technology code describes the following product features:

- geometrical shape,
- shape complexity,
- product representative dimensions,
- representative quality features,
- type of material,

- manufacturing technology,
- main application.

Hierarchical code is based on the tree structure. In case of codes of chain structure for representing information on a part, matrixes are used. Hybrid structure combines two of above methods using their most functional features fig. 8 [16].

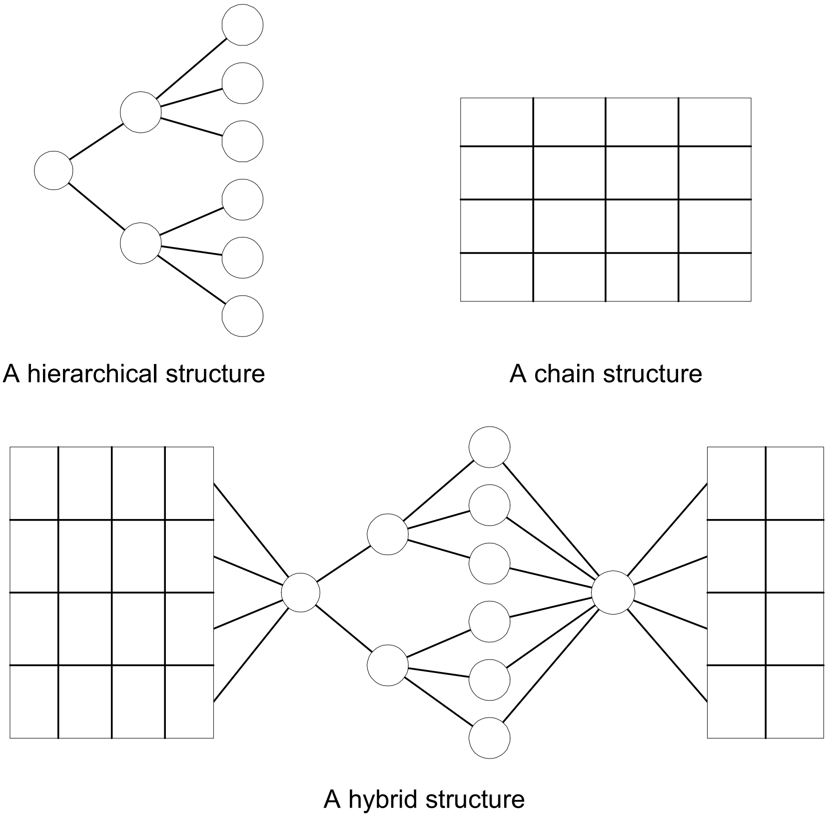

Fig. 8. Structures of codes used in Group Technology [16]

Thus far many classification and coding systems have been developed, chronological specification of more important ones is presented in the table 2 [17].

Table 2 System of coding and classification in Group Technology [17]

Year	***Name***	***Country of origin***	***Structure***	***Number of characters in the code***
1965	NITMASH	USRR	Hierarchical	15
1967	VUOSO	CZ	Hierarchical	4-6
1969	PERA	Great Britain	Hybride	3 + vectors
1969	Brisch	Great Britain	Hierarchical	4-6
1970	OPITZ	Federal Republic of Germany	Hybride	9
1975	MICLASS	The Netherlands	Hybride	12 master
1980	Part analogue	United States of America	Hierarchical	4-6
1980	DCLASS	United States of America	Hierarchical	8
1986	CAMACS	Great Britain	Chain	16x11 Matrix
1990	FORCOD	United States of America	Hybride	11

Examples of classification and coding systems [3], [18], [19]:

- **Toyoda** – developed in Japan. This code uses 10 digits.
- **OPITZ classification system** – had been developed by H. Opitz from the University in Aachen and is probably the best known

system of classification and coding. The OPITZ system uses decimal, hybrid code. The base code composes of nine characters, which can be expanded with next four characters (e.g. 12345 6789 ABCD).

- **CODE System** is part of classification and coding system developed by American company Manufacturing Data System, Inc. It is a hex code, constructed out of eight characters. Each character can have sixteen different values, which are used for product properties description.
- **MICLASS System** is a hybrid code, composed of twelve characters.
- **DCLASS Code** is a decimal code, built out of eight characters divided into five segments.
- **Tekla** – developed in Norway. Constructed out of 12 digits.
- **NITMASH** – developed in USSR. Hierarchical coding.
- **Brisch** – developed in Great Britain. Computer system without a constant code structure.

Using classification and coding systems yields the following benefits [3]:

- **Accelerates design process**. When new products are being designed, which are similar to products designed earlier data saved in database could be accessed under condition, that the product was appropriately coded earlier. Through modifying data, documentation for a new product can be swiftly obtained. Such action to a great extent reduces costs related to product preparation time for production.

- **Accelerates the process of creating technological documentation**. Technological plan describes the order of operations, to which product must be subjected and in what machines those operations need to be performed. The order of conducting those operations depends on two factors:
    a) technological requirements (order of performing an operation before others),
    b) possibility of performing individual operations in appropriate, available machines.

  Designing a technological process is a tall order, but thanks to application of coding and classification systems it can be simplified. A technologist creating technological process for a new product can use an already existent project for a similar product.

- Facilitates production scheduling. By appropriate production designing we can shorten the reset and tooling times of machines, what allows for effective utilisation of machines and increase in production efficiency.

4.2 Creation of workcells

The fundamental step during implementation of cellular form of organisation of production is identification of appropriate workcells. Having the specification of all parts produced (knowing their technological process, flow of material during production, volume of production batch, setting time of machines tools, times and estimated annual demand) and available machinery, parts can be classified into families, and planning of manufacturing process should allow for minimisation of production costs – fig. 9.

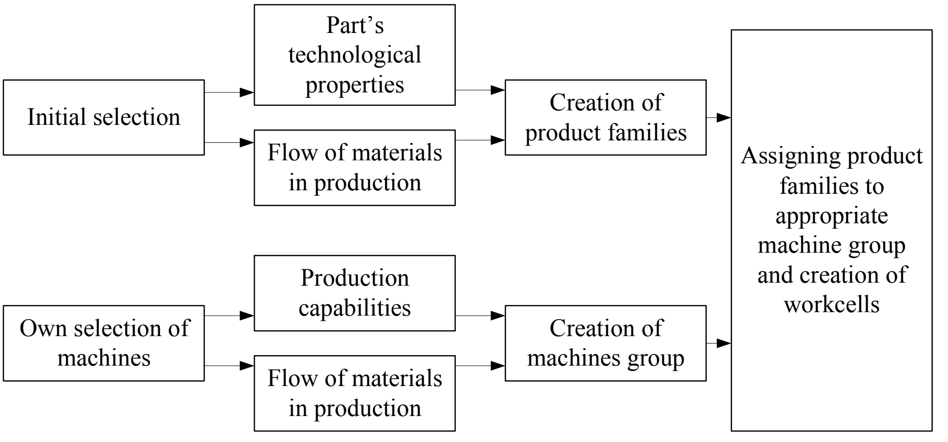

Fig. 9. Process of designing workcells

The following methods of creating workcells can be distinguished:

- **Observation methods** – visual appraisal of physical features of processed items and identification of features common within a given group. It is a low-precision method and used rather in the preliminary phase. This method's advantage though, is the fact that it is a quick method and relatively cheap, but requires utilisation of employees' knowledge (technologists') possessing relevant experience in designing technological processes. In many cases this method is being used despite the fact, that such approach in GT often provides imprecise and inconsistent results. Nevertheless it is possible to obtain very good results in designing workcells, especially when designing production lines. The quality of obtained outcomes is dependent however on knowledge, commitment and display of one's own initiative by employees.

- **Classification and coding of products.** Workcell designing by means classification and coding systems requires completion of three steps.

  First step is identification of products, by determination of category of products sharing common technological features. Properties and dimensions of individual categories are considered.

  Second step is alphanumeric coding of individual parts, and that code is represented by information about the coded product.

  Third step is classification of products into product families, which have similar technological properties, by means of using coded data on designing and technological properties of individual parts.

  It is important, that the codes identified parts in a manner allowing for identification and obtainment of coherent data. In those systems a special code is attributed to particular features of a part depending on e.g. is that part cylindrical or conical, is it threaded, has it got any holes, is the heat treating required etc. This part of the production preparation process demands paying loads of attention and sacrificed time in order to precisely classify all parts. Conducting research into features characteristic for machining processes or their technically-constructional parameters are underling the classification and coding methods. Disadvantage of those methods is the fact, that creation of codebase for products entails time outlays and is labour-intensive. Moreover code often provides limited information about the product construction, as well as about the ways of its manufacturing, hence there is a need for constant, active engagement from experienced employees in the process of designing and manufacturing of a product. For creation of workcells one can use an already existing in enterprise classification and coding system. In case of lack of it, its introduction, exclusively for designing workcells is unprofitable, because there are other methods of designing workcells which are less time and cost-intensive.

- **Production flow analysis** – determines simultaneously families of parts and groups of machines though material flow analysis in production process. Production flow analysis groups into families products, having similar technological processes and requiring machining in the same machines, and also requiring combination of those machines into a machining cell. Method of production process course analysis concentrates on similarities (conformity) in technological operations. As base material for analysis are used data derived from technological and planning documentation. The analysis can be divided into four fundamental stages [20]:
  - construction of databases: accumulation of data, combination into sets, items subject to analysis from the planned production process's point of view, coded description of every element.
  - element sorting: creation of subsets according to conformity of technological operations.
  - visualisation of production process course: graphical representation of outcomes of sorting operation.
  - parts grouping.

  Techniques of production flow analysis have got the following advantages:

- allow for designing a machining cell quicker and at relatively lower effort than if used was classification and coding system,
- because production flow analysis is based on material flow in production process, those techniques are focused solely on current production methods, using existing machinery and tool system,
- production flow analysis provides production reorganisation and obtainment of benefits resulting from cellular form of organisation of production process at low outlay of investment costs.

In the initial stage of analysis a matrix of ***MxN*** is formed, where:

- ***M*** – number of machines,
- ***N*** – number of parts produced.

If the matrix is of small proportions, products requiring similar technological operations, can be grouped together, as a result of manual sorting of rows and columns. If the Machines-Parts matrix is larger, then for sorting the matrix are used the following methods:

- *Rank Order Clustering* method*,*
- *Bonding Energy* (BE) method,
- Row and Column Marking method,
- methods based on computing Relationship Coefficient (RC),
- matrix method.

In order to obtain good results of conducted analysis, one should be acquainted with precise flow of materials in production process for every manufactured part. Some products might not match a family, because they require a special operation. In order to make decision about adding an additional machine, an additional analysis is required.

4.3 Arrangement of machine tools inside workcell

In previous chapter methods of creating a workcell were presented. As a result of calculations the number of cells and allocated to them stations are obtained. The next step of designing such LAYOUT plan is to solve the problem of station arrangement inside every cell.

Wherever machines in quantity of 1 to 15 units are grouped into a workcell, the U-shaped workcell is recommended, presented in fig. 10. Machines were arranged as follows, in order to achieve very tangible objectives such as improvement of conditions of their service and possibility of high automation for that matter. U-shaped workcell holds numerous advantages. It provides high flexibility, and employees operating it are prepared to perform a broader range of tasks. Those tasks may change and their quantity may decrease and increase while maintaining the core production attributed to the given cell. Employees are responsible for more than one machine (pairing of machines), therefore usefulness of employees ceases to be narrowed down to only operate a single machine. Close contact and cooperation between employees in U-shaped cells renders productivity to increase at lower rate of downtimes (idleness), prevents reduction in quality, decreases level of inter-operational stocks and value of production in-progress.

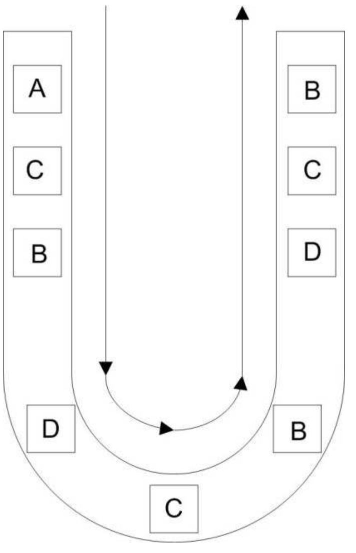

Fig. 10. U-shaped arrangement of machines
A - lathe, B – milling machine, C- drill, D- grinding machine

Nowadays increasingly frequently machines and devices are arranged into the “U” letter shape. It is a certain opposite of linear devices setup in flow production lines. However that type of setup has got several advantages [21]:

- is flexible in terms of blue collar staff, because it is easier to move around employees to perform various works,
- the setup provides improvement of morale and satisfaction from performed work, through possessing by employees many qualifications and appropriate training system,
- improves transparency of production process and facilitates supervision over it,
- the only range of supervision needed from cell’s outside is control of IN and OUT times.

- control over flow inside the cell is performed by foreman or cell's employees,
- utilisation of Group Technology in U-shaped cells, finds its reflection in form of implementation of the JIT concept.

Figure 10 presents a U-shaped workcell. Material necessary for manufacturing the product enters the cell, progresses through it and leaves the cell in form of a finished product.

4.4 Costs as a criterion of process optimisation

In this chapter is presented one of the most important aspects of an enterprise's economic activity, namely analysis of costs related to production process and influence of allocation of workplaces on level of costs. It is an immensely vital factor, which needs to be precisely analysed before initiating construction of manufacturing system.

Manufacturing system should be created in a fashion ensuring a comprehensive and constant surveillance in real time both over flow of information and materials necessary for conducting the production process.

One of the most prominent issues when designing a workcell is grouping of machine tools and machined parts. The hitherto approach towards this matter didn't take into account such essential factors as the order of technological operations and required production batch size. New methods of organisation of production do take into account the technological process (order of technological operations) and arrangement of cooperating stations as factors directly influencing costs of material transportation within a workcell, as well as between workcells.

Grouping of machines focuses on actions aimed at [22]:

- creation of machining cells, where items are manufactured “ready-made”,
- determination of plain flow of parts processed by a workcell,
- elimination of “recurrences” and intersections of part machining routes,
- minimisation of investment outlays related to purchases of machine tools of the same kind,
- obtainment of appropriate degree of machine utilisation,
- obtainment of appropriate production system efficiency,

One needs to pay attention to the fact, that the order of technological operations is directly connected with costs of transportation. In strict relation with that issue remains also the volume of production batch related to production in-progress stock and frozen capital. Hence the methods of allocation and grouping of workplaces should also take into account those factors in particular and should provide an answer to the question of how to organise the manufacturing process in order to lower costs of transportation and costs related to production in-progress stocks.

Analysis of costs related to flow of materials with reference to creation of workcells is based on several assumptions [22]:

- costs of transport between cells are connected with the physical displacement of parts, loading and unloading and coordination of a cell’s work. The perfect situation would be manufacturing “read-made” parts within the confines of a given cell.
- costs of transportation inside a cell are dependent on the magnitude of the batch machined and allocation of stations

within the cell. They are also related with the direction of flow of parts through the cell, recurrences and intersections of flows. Those last two factors in particular significantly increase the costs of intracellular transport.

- costs of omitting a workplace incurred when some parts are not machined in all machines within a given cell. It contributes to process delays.

The magnitude of the batch subjected to machining plays also an important role in determination of manufacturing costs. Obvious is the fact of increasing transportation costs with the increase of the quantity of parts processed in a given batch.

In an ideal system of cellular form of production there is no flow of material between cells, but in reality it is a very difficult task to form machine groups in such a way, that there was no flow of material between them. Bearing in mind that practical constraint, the analysis should try to formulate such machine groups, which would minimise the intracellular flow of material. Also an important task is minimisation of costs related to intercellular transport of material, and that requires designing LAYOUT plans for each of cells. One of possible ways is firstly identification of workcells and parts, which are going to be manufactured there, secondly LAYOUT of machines in workcells has to be designed and the LAYOUT of the cell itself as well.

The profitability of purchasing an additional machine for a workcell needs to be frequently considered, in order for the part manufactured to be produced in that cell from start to finish, or is it rather more profitable to e.g. automate the transport between two cells, where that part is being produced, or perhaps create a special buffer, from which materials for production of a given product are going to be collected. An additional machine tool of the same kind can also be purchased, in order for the part to be completely machined within a single cell.

Allocation of machines in the cell and the cell’s itself can be planned in such a way, that machine tool was a constituent of both cells. In that manner we avoid doubling of machines of the same kind.
Other factors which need to be taken into account are:

- size of inter-operational stock,
- machine’s depreciation,
- cost related to the time of setting up the machine.

If those costs are taken into account during designing of workcells and attributing part families to those cells, the end result not only will allow for better control over production, but also will considerably decrease costs of production.

Improvements of inner transport provide the fastest and the cheapest route to better the profitability. Thus one has to strive for reduction of transport operations, which increase the process cost. When solving problems connected to transport one need to take into account the design of workplace allocation structure and data related to the project.

5 Methodology of designing a manufacturing system

Methodology of designing allocation of workplaces presents the diagram in fig. 11. The course of work was divided into stages. Their detailed description in located below. Subjects of designing in presented methodology are production-subjective cells. Manufactured in these cells products have got similar or different technological routes. It determines the presence of complex coupling network between elements of production system i.e. occurrence of recurrences and workplace skipping. Presented methodology is applicable in designing new production systems or reconstruction of existing ones.

STAGE 1 Collection of necessary data and definition of design task

At the first stage gathering of information takes place, which is necessary for defining the design task. The square one here is the course of manufacturing processes. A technologist developing the technological process defines technological operations to which apart from tools, instruments, parameters, description, sketch and norm he also attributes the workplace. In that manner he determines the technological route for a given process. The material is passed between stations until completion of a finished product. All those activities can be computer aided.

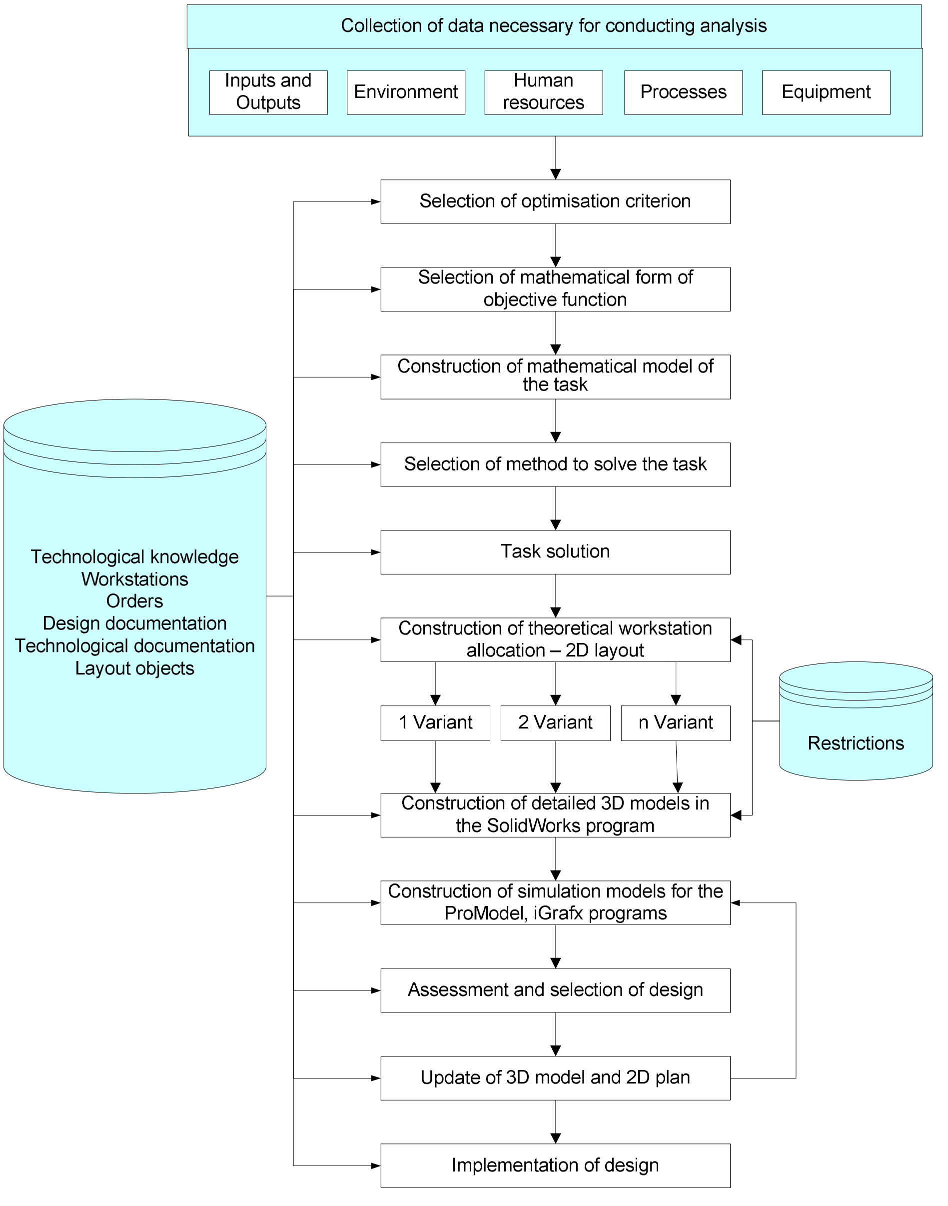

Fig. 11. Methodology of designing workplace allocation

Production system designing requires at least two-level approach, where two fundamental tasks are solved consecutively [1]:

- selection of hardware equipment in terms of used technologies,

- allocation of chosen machines in production departments.

Additionally a range of essential data needs to be garnered such as [21]:

- organisational structure of enterprise,
- type of production system,
- multiplicity of staff and their qualifications,
- dimensioned sketch of the surface available, precise scaled drawings of surfaces' projections, thickness of buttresses, socles, dimensions of juts projecting from walls, switchboards, fuse boxes etc.
- localisation of existing installations or permanent constructions,
- deployment of existing office spaces, sanitarian areas etc.,
- volume of production, both current and enclosed in enterprise development strategy,
- type of technologies used, performed operations, their description, sequence and normative execution times, with indication to any operations of hazardous or special character,
- specification of equipment intended for performing operations together with specification of concomitant special requirements, electric power, devices of repair sets, safeguarding etc.,
- number and type of transport operations of material between workplaces, (it's convenient to aggregate that information in form of oriented matrix of transport relationships),

- lead times, aging times, stabilisation times etc., during the manufacturing process,
- quantities and sizes of operational stocks at each workplace,
- dimensions of main storages, finished products storages, are dependent on used delivery system and used dispersal ranges,
- required communication links and emergency exits,
- any special requirements, for example burglar alarms, alarm system etc.,
- spare devices or premises which need to be included in the plan.

All the above information required are perceived as necessary prior to commencing workplace arrangement designing. Obviously the characteristics of every production or services process require an individualised approach.

STAGE 2 Selection of optimisation criteria

The literature concerning the subject matter lists a range of available criteria of correct allocation of objects and as far as allocation techniques regard organisation of production or areas of examining work methods, the allocation process itself has got a creative character, impossible to conclude in a final and irrevocable manner, where experience plays the biggest part. Below are listed several most important criteria, which ought to be fulfilled by a given production structure. They are [21]:

Maximum flexibility: giving possibility of easier modification depending on changing circumstances. One should especially pay attention to an object's tooling to be sufficiently in working order and easily accessible installations.

Maximum interdependence: delivery and collection processes should be organised, so that they would provide maximum satisfaction of cooperating departments' needs, arrangement should be visible also from the global, not only local point of view.

Maximum space utilisation: production organisation should be treated as three-dimensional objects, wiring, pipelines and other installations requisite in the production process should be led over the heads of employees, if we use cotemporary storing devices we can fulfil that postulate at ease.

Maximum transparency: one needs to strive for provision of constant visual control over entire personnel and conducted processes. It is often quite difficult to fulfil this criterion, especially in situations, when already existent objects are taken over.

Maximum accessibility: any operational and service points should be easily accessible, if obstruction of repair service or maintenance points is unavoidable then one needs to aim at installing a mobile device.

Minimum distance: any displacements should be made only when it is necessary and take place at the shortest distance possible. Transport operations are only increasing costs without adding any value.

Minimum transhipments: if transhipments cannot be avoided, then their number has to be reduced.

Minimum inconvenience: bad lighting conditions, draughts, excessive sun exposure, noise, vibrations – all those phenomena need to have actions taken against them and their influence on people minimised.

Inherent safety: none of employees can be exposed to any form of danger resulting from incorrectly organised production system.

Maximum protection: protection against fire, dampness, heart attack etc. they should be taken into account already at the stage of allocation designing.

Effective courses of processes: material stream flows in production process should not intersect with each other, one-way flow through objects should be maintained, arrangement contributing against that notion leads to serious difficulties, sometimes to chaos in organisation.

Identification with the workplace: wherever it is possible, an employee should have his workspace allocated.

Most commonly used in designing workplace allocation is the savings code of conduct [23]. It means searching for solutions guaranteeing a particular degree of goal realisation (e.g. determined production tasks) at minimum construction and system maintenance outlays. Hence the most frequently used criteria of solution's assessment are transportation costs, values of ratios describing transportation tasks (length of transportation routes, transported volumes etc.), cost of workplaces' installation, costs of production floor and other.

STAGE 3 Construction of mathematical model.

At the third stage, description of the task being solved takes place in form of a mathematical model. There are multiple mathematical models of the allocation task. Use of a particular one depends on specifics of the task being solved [23]: type of production structure and coupling network, number and type of constraints, and also assumed optimisation criterion. Last of aforementioned factors decides about the form of objective function, being the main element of a task's mathematical model.

Predominantly formulated and solved are tasks with a single optimisation criterion. The necessity of fulfilling many, often opposing goals, causes allocation tasks to have to be formulated as multi-criteria.

STAGE 4 Task solution.

At the fourth stage the posed task is solved be means of optimisation methods. Selection of the method of solving the allocation task is determined by many factors. The main one being the mathematical form of the task.

STAGE 5 Construction of theoretical LAYOUT plan.

Based on results obtained from solving the task (Stage 4) a theoretical LAYOUT plan is constructed in form of a graphical model. Due to existing restrictions, which were not taken into account in the mathematical model many variants of theoretical arrangement of workplaces can be developed. The usefulness assessment of individual solutions will take place at subsequent stages.

In case of unfavourable appraisal there is possibility of reverting to preceding stages of the methodology, in order to e.g. reformulate the task and its repeated solution. It may also turn out, that the only radical manner of obtaining an acceptable solution is to improve the flow of material through changes in production structure.

STAGE 6 Construction of a detailed LAYOUT plan.

Based on a chosen, real variant of theoretical allocation a detailed design of workplaces' arrangement is developed (in several variants). To build detailed allocation plans one can use graphical editors.

STAGE 7 Construction of simulation models and running the simulation and optimisation of production process.

By simulation and optimisation of production process we understand carrying out various tests upon a model, under different scenarios, where we determine particular optimisation criteria of obtaining satisfactory to us results, for precisely determined values of factors influencing the model's behaviour.

Simulation is a technique serving as an imitation of an entire system's functioning or just imitating certain situations (economic, military, mechanical, etc.) through use of appropriate models or devices in order to obtain information, or for didactical reasons. [24]. Computer simulation facilitates analysis and optimisation of a newly designed process prior to its implementation, thanks to which we avoid costs related to system implementation, which could have been incorrectly designed.

6 Designing arrangement of workplaces using computer systems

Commonly known are the following computer systems aiding the process of designing allocation of workplaces plans [3], [21], [25], [26], [5], [27]:

- CRAFT (Computerized Relative Allocation of Facilities Technique) – written in years 1963/64 by Armour, Buffe and Vollman. It adopts as criterion minimisation of total transhipping costs,
- CORELAP (Computerized Relationship Layout Planning),
- ALDEP (Automated Layout Design Program),
- RMA Comp 1 (Richard Mather and Associates),
- VisFactory,
- PREP (Plant Relayout and Evaluation Package),
- COFAD (Computerized Facilities Design) – was created after the CRAFT program had been modified. At optimisation of allocation it takes into account costs related to used means of transport,
- PLANET (Plant Layout Analysis Evaluation Technique) – As optimisation criteria it adopts minimisation of inter-operational transport,
- MAT (Modular Allocation Technique),

- BLOCKPLAN,
- EON Planner,
- Delmia QUEST and others.

Some of those solutions are obsolete and offer a very limited functionality. They operate in text mode and as the result of optimisation they present only the mutual arrangement of objects. The obtained result is very simplified and requires further analyses. Contemporary systems work with graphical user interface, and allocation plans are designed as spatial models. Such representation of production system facilitates its further analysis. Generated models include not only workplaces, but also other elements of modern production systems, means of transport, storehouses, network elements and others. Additionally available are tools for visualisation of material flow.

The fundamental constraint of those solutions is the fact, that they do not offer integration with CAPP systems and the majority of them work independently of network connection. A contemporary solution should be based on computer network with a central database available in different cells of enterprise (fig. 12).

Data necessary for designing a production hall model are courses of manufacturing processes. That information is stored in CAPP systems' databases. Allocated to technological operation workplaces by linking them with appropriate graphical models can be used for constructing a production system.

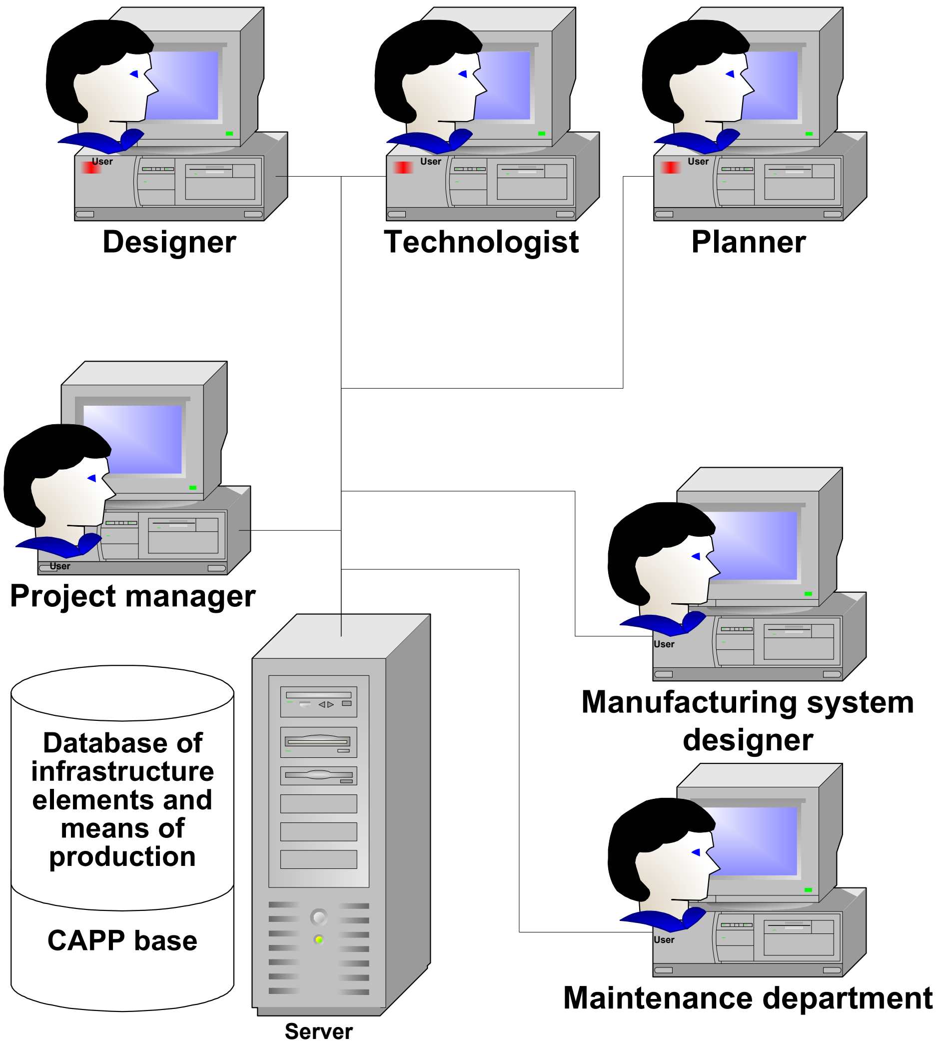

Fig. 12. Network model of computer system with central database of means of production

Technologist designing technological operations has to allocate to each of them an appropriate workplace. Those could be e.g. machine tools, quenching stations, quality control stations and other. In case of complex production systems and multi-operational technological processes, selection of workplace of adequate technological capabilities may prove troublesome.

That problem applies to machine tools in particular. Machine tools have got different technological capabilities, different ranges of machining parameters and standard equipment. Designing technological processes in CAPP systems can be improved through elaboration of models of data describing technological data and operating features of machine tools. A computer application should provide quick selection of a workplace according to assigned criteria. An example here could be linking a workplace with a technological operation. The application makes available only those workplaces where a particular operation can be executed (e.g. selection of grinding operation will make available only grinding machines).

Application for managing workplaces can be also used by people, who are responsible in an enterprise for traffic maintenance. In the database that person can store information on dates of planned inspections and the history of repairs and maintenances of a given machine tool. Hence the system can signalise with a certain advance, that a given machine tools is going to be excluded from the traffic because of check-up or repair. The advance should be defined in such manner, that it would be possible to garner (purchase) appropriate materials necessary for maintenance or inspection of a machine tool. The person responsible for technical condition makes an appropriate entry in the system. In that case the planner has to divert operation onto a substitutive workplace.

6.1 Designing arrangement of a workplace with presentation in 2D view

In fig. 13 is presented in simplification a developed computer system module aiding hall design.

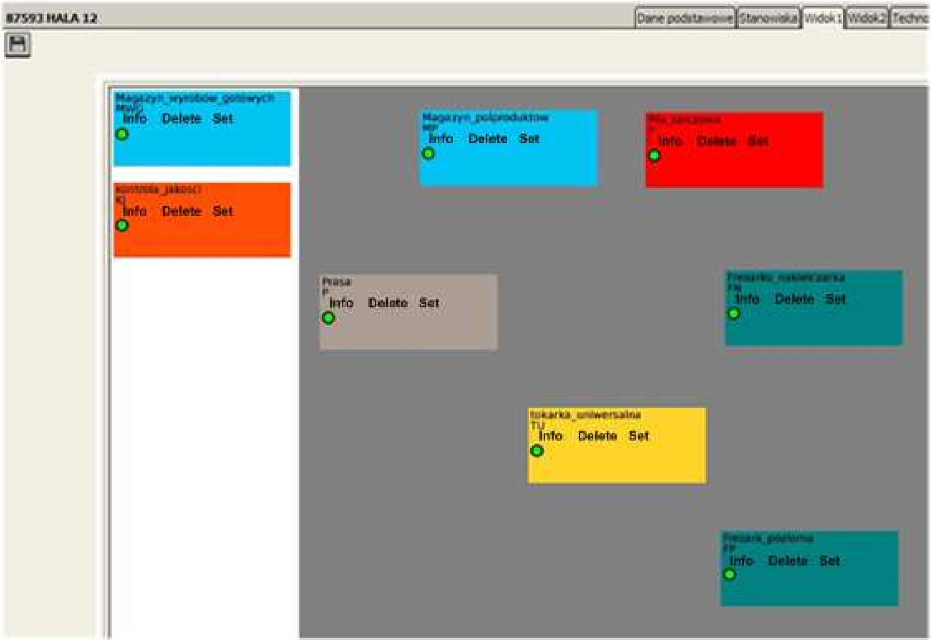

Fig. 13. Simplified production hall designing–2D view

On the left hand side in fig. 13 are presented workplaces, which can be situated within the hall. They are: “quality control” and “finished products storage”. On the right hand side we see 6 workplaces, which have got already an attributed localisation on the shop floor.

Addition of a workplace to the hall takes place by dragging it from the bar to the left onto the hall floor or by choosing the option “set”. After definition of coordinates for workplace’s localisation click the “Set” button – fig. 14.

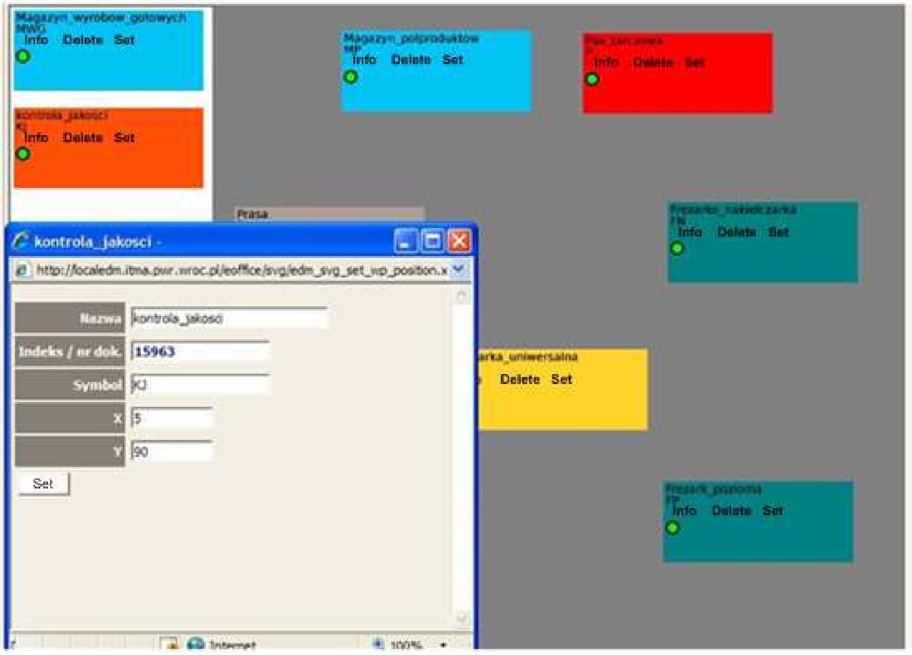

Fig. 14. Adding workplace to the hall by defining coordinates of its location

The workplace will be situated within the area of the hall. The position of the workplace can be modified dynamically through dragging and dropping with the mouse pointer. Positioning alteration needs to be confirmed by clicking the "Save" icon.

The workplace situated on the hall can be removed from it by clicking on it the option "delete". Green lamp beside the station demonstrates that the station is operational and available. In case of failure it is going to be marked red. In case of inspection blue. Stations' statuses are configurable. The signal colour scheme can also be modified. In fig. 15 is depicted an exemplary hall design – milling machine FWD-32 has got the status "failure", the milling machine FXJ-40 is being inspected.

Fig. 15. Example of designed hall with presented statuses of workplaces

Clicking on a given workplace (the word "info") allows obtaining more information on it. It allows access to detailed data and other tabs (fig. 16).

Fig. 16. Detailed data about a workplace – 'info' option was selected

From the level of basic data it is possible to change statuses of workplaces. After saving changes the status is updated in the hall view.

6.2 Designing arrangement of workplaces with presentation in CAD 3D system

If during construction of production system additional conditions and restrictions resulting from building's equipment (e.g. common power supplies for machine tools, special foundation, limited load bearing of ceilings), health and safety (e.g. required distances between stations) and other must be taken into account the functionality of presented application for 2D presentation is insufficient. One should use an application, which will allow for generation of 3D plans and will allow for a broader take on the problem of designing production systems. Analysis of capabilities of the Solid Works CAD system proved, that it possesses the functions, which allow for constructing a hall model. Additionally it has the possibility of writing own programs in the Visual Basic language using the API.

In order to build a 3D model of a hall, the module for creating assembly documents in the Solid Works system is used. Inserted components can change their localisation along three axes. In case of designing production halls it had been established, that the hall (floor) is located at the z=0 height. During insertion of 3D models of workplaces into the assembly, the application Layout-3D automatically adds the relation “Merged” between the surface representing the area occupied and the main plane for the entire assembly. Such constraint means, that when moving stations by means of a mouse, the Z coordinate does not change. Generated by the system mates are shown in fig. 17.

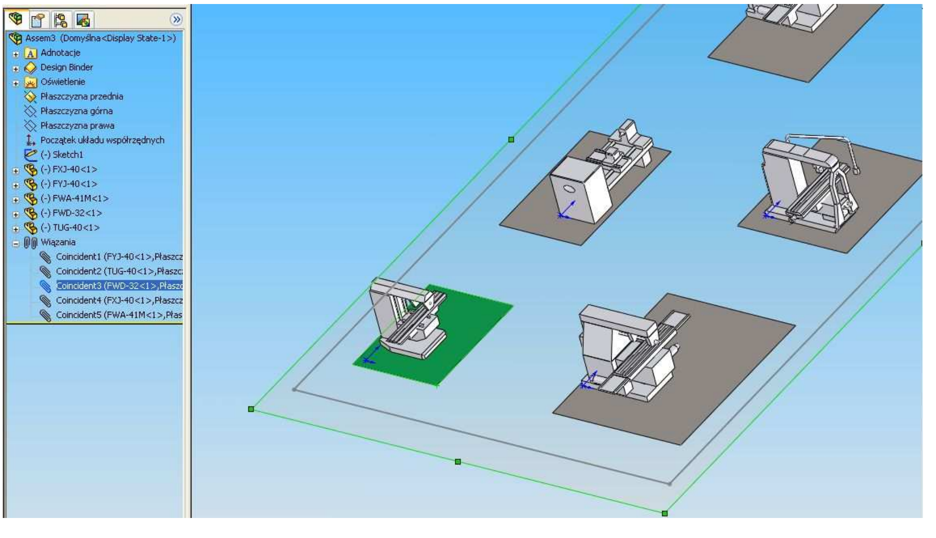

Fig. 17. Mates generated by the Layout-3D application

Information on workplace's localisation within the production hall is available under the "Location" option. Those are X and Y coordinates. Alternation of location's coordinates and clicking on the "Save" icon causes displacement of the workplace.

Computer systems ought to be used very cautiously. The solution suggested by the computer should be considered as preliminary for further consideration. Computer cannot make decisions for us in terms of arrangement of objects.

7 Computer systems for simulation of production processes

Available in the market systems for simulation (e.g. ProModel, iGrafx) rely on a LAYOUT plan constructed by the user and cannot optimise it. They only analyse what is going on in the production system, provided that workplaces are immobile. Furthermore dimensions of workplaces are irrelevant along with their workspaces. Thus it is impossible to build a model of a real size.

7.1 iGrafx system

The iGrafx system, product of Corel is a consistent system of diverse graphical tools dedicated for enterprises. Graphics increases the effectiveness of communication through visualisation of content. iGrafx system provides tools adequate to needs and possibility of utilising them by certain users at the enterprise level. Common base resources for all elements of the system in tandem with common formats of graphical documents allow for sharing graphics irrespectively of application, in which they were created (all applications of the iGrafx system cooperate with each other at the same level of integration as MS Office applications do). At the same time advanced, often unique functions included in modules dedicated to specialised users, guarantee satisfaction of their even most sophisticated needs. Components of the iGrafx system are intended for working in network and have got built-in mechanism limiting work of administrators connected with managing them. iGrafx program is intended for aiding planning and creation of organisation of labour in firms and enterprises. The program allows for process modelling through:

- their graphical visualisation,
- analysis and simulation of their course.

Outcomes of simulation are presented in reports featuring different criteria e.g. time, costs, used resources.

Modelling of processes facilitates making correct decisions, because allows for answering the questions:

- How much time do individual process stages take?
- What should be the schedule of individual activities?
- Where are located bottlenecks?
- What data is necessary (input) and outcomes (outputs) of activities?
- What is the availability and utilisation of resources (people, machines, devices)?
- What is the cost of processing a single transaction?

Thanks to that the designer can:

- find and indicate what can be improved in work organisation,
- find and indicate mistakes before they occur in reality,
- compute statistics regarding the time of work, costs, resources utilisation.

Processes are reproduced in a very realistic way. It possible to i.a.:

- determine acceptable by law (legitimate) number of overtime hours,
- indicate National Holidays and bank holidays (days off work),
- assign certain actions to designated time points,

- introduce probability of failure or indisposition of individual process participants.

Results of the analysis and simulation of process courses along with a graphic representation of the scheme, can be saved in form of HTML and send out to all interested people via the company's Intranet.

7.2 ProModel

ProModel is a system for simulation and analysis of production systems of different types and sizes, working in the Windows environment. ProModel is an easy to use, complete and flexible tool, moreover allows for realistic simulation. It can be customised according to individual needs by expanding own graphical libraries containing workplaces, production resources etc. As a discrete event simulator, ProModel is intended above all for modelling discrete parts of production systems, although it can model continuous industrial process, e.g. filling and emptying the tank with fuel. ProModel allows for simulation of processes with precision of from 0.1 hour to 0.00001 s.

Construction of a model takes place in the following stages:

1 – Construction and definition of a virtual model of workplaces allocation of examined manufacturing system

In the *Locations* module (fig. 18) we present standing points of a manufacturing system, through which pass manufactured elements.

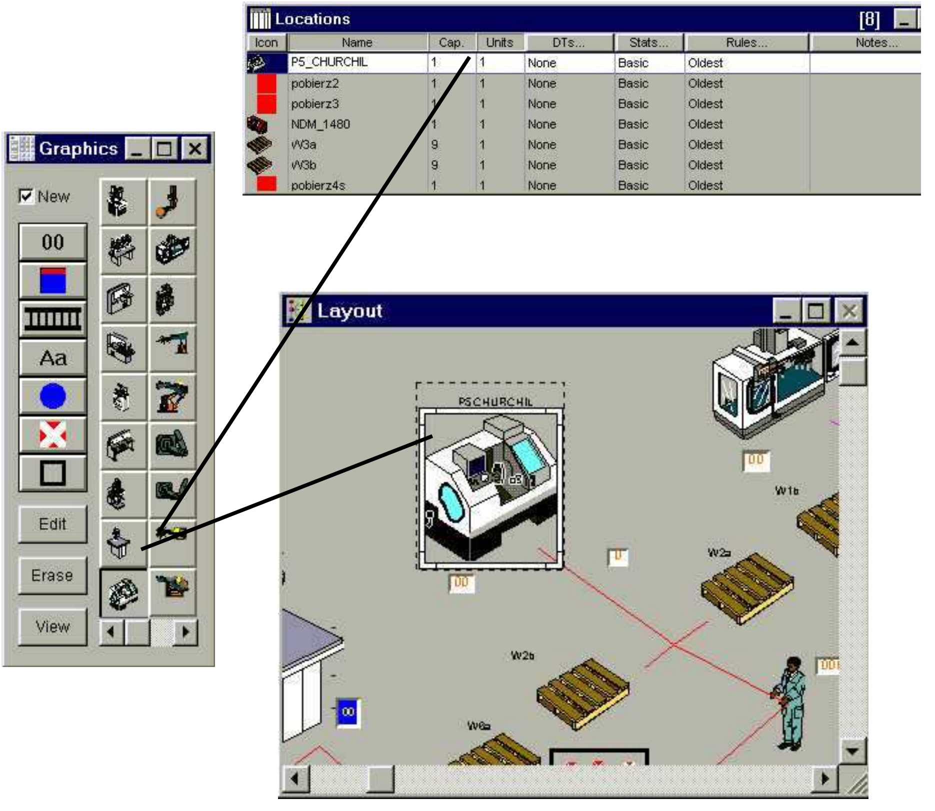

Fig. 18. Locations module – construction of virtual model of analysed production system

By the name standing point we understand storages, workplaces, transport system, buffers etc. Those points are represented in the graphical window by icons. Icon database allows for selection of appropriate reproduction a given station in the graphical window. All points have got names assigned and identification numbers.

2 – Definition of production entities

Production entities describe all elements of production process, such as parts, product or even technical documentation. Individual materials can be grouped together into a whole, e.g. when we have several boxes with products resting on a single pallet, or can be consolidated into a new, single value, e.g. in case of fitting a tyre to a wheel, or we can create new materials out of existing ones, just like in the case of delivering some medium (e.g. compressed air) from one pipe to several places.

Every kind of production entity has got a name assigned, which represents a given entity during graphical animation.

3 – Definition of connections between process elements – *Path Networks*

Transport route – *Path Network* – is used to describe movement of material and resources between individual stations, depending on the order of performing technological operations or tasks assigned to employees. Along one transportation route any kinds and quantities of production entities and resources can move. To resources and transport routes we assign time and speed of movement along the route of transport.

4 – Definition of system personnel

In the *Resources* module we assign to the process personnel in form of employees, technical equipment, used for:

- transport of production entities,
- performing technological operations.

Resources (personnel) are composed of one or more entities having characteristic features in common such as for example employee groups. Every moving within the system resource is assigned to a particular transport route.

Depending on whether resources are moving within the system or not, they are static or dynamic.

5 – Definition of production process.

In the *Processes* module we describe behaviour of the process in time. We define flow of materials through the system and where technological operations upon a given material are performed. Material can be transported to the next place, only when the capacity for a given location is reached.

6 – Definition of process feed.

For description of manufacturing system feed is responsible the *Arrivals* module. Delivery is defined as any kind and size of batch of material entered into the production system. Deliveries can be set in accordance with production plan, in periodic intervals, in ascending or descending quantity according to a strictly determined pattern, or as a result of any event taking place in the model. If acceptable by the system capacity delivery is exceeded, it is plainly rejected from it.

In ProModel suite, application performing optimisation process is **SimRunner**.

The first step for analysing the model subject to simulation is the analysis, which factors influence the system behaviour and what is the extent of that influence.

SimRunner (fig. 19) allows for measuring effects of changes, at altered influence extents of a particular system factor. By conducting a series of experiments, it is possible to calculate effects of value alteration of particular factors and selection of optimum value of the objective function.

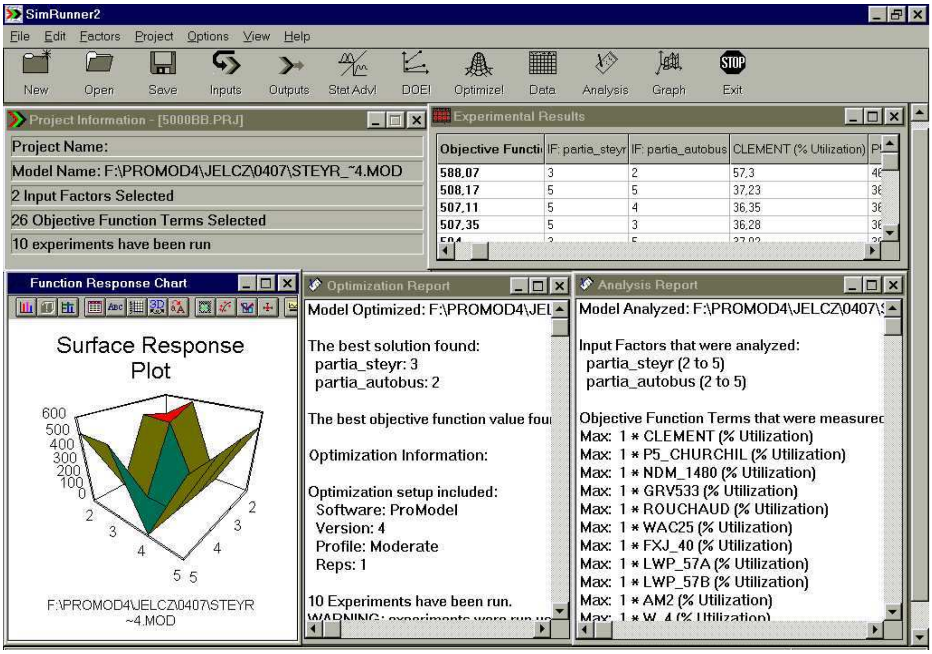

Fig. 19. SimRunner – module of simulation and optimisation of the examined model

The *Output Module* application allows for analysis of statistical results of conducted optimisation tests (fig. 20). Thus we have the possibility of choosing the most favourable values of factors influencing the model. *Output Module* prints results in form of charts.

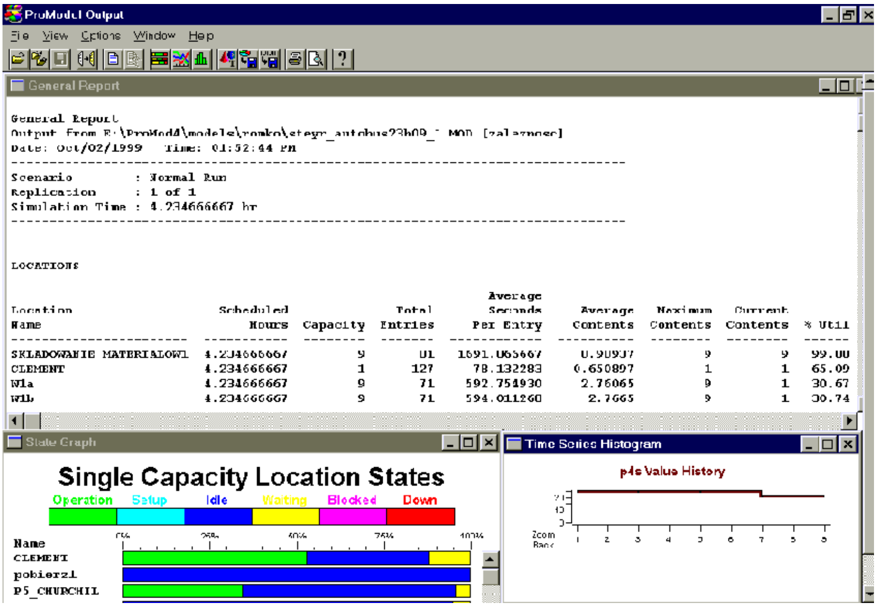

Fig. 20. Output Module – analysis of statistical results of conducted simulation

The final report includes extensive statistics regarding workplaces, production resources, items manufactured in the modelled system. Separate detailed statistics are owned by workplaces, production resources and products, e.g. for products and raw materials is computed the percentage of displacement time, lead time for production resources, in operation and blocked.

8 Methods of optimisation of workplace allocation

Two groups of methods can be distinguished:

- for cellular structure,
- for structure without division into workcells.

Below are presented several methods, which allow for obtainment of workplace allocation propositions. The Rank Order Clustering method applies to cellular structure. The CRAFT method can be used for systems without separated cells. There are many more optimisation methods. Their description is available in literature.

8.1 Rank Order Clustering Method

This method assigns a binary value to every row and column, transposes rows and columns in descending order of their binary values, on that basis equipment of future workcell and produced there parts is determined. The method is very simple and easy in application. In the ROC method six basic steps have to be taken [3]:

Step 1 – Assignment of binary value

$$WB_j = 2^{m-j},$$

where: m – number of machine tools in every column *j* in the part-machine tool matrix.

Step 2 – Determination of decimal equivalent DE for every binary value in the row *i* following the formula:

$$ED_i = \sum_{j=1}^{m} 2^{m-j} a_{ij}$$

where: a_{ij} – matrix of machine tool-part relationships

Step 3 – Setting of rows in the order of descending values of the decimal equivalent DE. If further row transposition is not needed, the algorithm execution has to be stopped, otherwise proceed to the step 4.

Step 4 – Every row in the matrix needs to have a binary value assigned

$$WB_j = 2^{n-i},$$

where: n – number of parts

Step 5 – Determination the decimal equivalent DE for every binary value in the *j* column following the formula:

$$ED_j = \sum_{i=1}^{n} 2^{n-i} a_{ij}$$

Step 6 – Setting of columns in the order of descending value of their decimal equivalent. Order columns following the DE values for each column. If there is a need of further column transposition, proceed to the step 1.

The downside of this algorithm is the fact that the final solution depends on the initial arrangement of rows and columns in the matrix.

8.2 CORELAP method (Computerized Relationship Layout Planning)

This algorithm differs substantially from previously presented allocation methods. The majority of methods assumes as optimisation criterion only one type of relationships between elements of production system, usually those being transport relationships. Transport relationships are not the only relationships between workplaces. Many issues take into account also other functional relationships of workplaces, amongst which we can include [4], [28], [23]:

- provision of appropriate personnel,
- effective supervision,
- enabling contact between employees,
- flow of documentation,
- technological relationships (e.g. using the same work stations),
- noise and others,

To appraise the total closeness rating a six-degree alpha-numeric scale was used (table 3):

Table 3. Six-degree alpha-numeric scale of total closeness rating [28]

Character scale	Total closeness rating	Numerical scale
A	Absolutely necessary	6
E	Very important	5
I	Important	4
O	Ordinary	3
U	Unimportant	2
X	Undesirable	1

CORELAP technique allows for inclusion of many kinds of relationships between objects. Selection of relationships, which are included is discretionary and depends on designer. CORELAP method [3], [4], [28], [23], [26] is approximate, stepwise and modular with unlimited possibility of choosing the place.

The starting point in the CORELAP method is the matrix of functional relationships of arranged objects. The idea dictates such allocation of objects, that degrees of required closeness recorded in the S^F matrix are satisfied, what means, that for example objects *i, j* of relationship strength A need to unconditionally stand next to each other, whilst objects *i, j* of X strength cannot be in any case neighbours.

For this method the following sum must be minimised:

$$Q = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} S_{ij}^{F} * L_{ij}$$

where:

SF_{ij} – degree of demanded *i, j* objects closeness according to six-degree scale

L_{ij} – distance between places of *i* and *j* objects allocation, where Cartesian distance measure was adopted

$$L_{ij} = \sqrt{(X_i - X_j)^2 + (Y_i - Y_j)^2}$$

In the CORELAP method calculations are made in two stages: determination of succession of arranged objects and selection of places of their localisation. Realisation of individual stages may take place serially or be parallelised. Objects are arranged in nodes of orthogonal net, which is usually presented in form of the *U* matrix. Its elements represent numbers of arranged objects. Set of identical elements, which are of equal values, creates the outline of object arrangement shape. Every element of the *U* matrix corresponds to a modular surface unit. Shape of the surface, where objects will be allocated can be imposed by entering for example the *a* parameter being the ratio of sides of the *U* matrix. Before commencing the relevant calculations the following activities are performed:

- Surface estimation (dimensions of the orthogonal net – *U* matrix) in modular units for allocation of all objects.
- Calculation for all objects sums of total closeness rating TCR_i according to the formula:

$$TCR_i = \sum_{j=1}^{N} S_{ij}^{F}, \quad , \quad i = 1, 2, \dots, N$$

- Creation of object list in the order of descending sums of closeness rating.

In the CORELAP method at every step only one object is arranged. All objects arranged according to non-growing sums of closeness rating are

C type objects, that is candidates for allocation. As first are arranged objects with the highest values of TCR. It is located in the centre of the net. Simultaneously it becomes a type *W* object. It is sequentially checked if there are amongst remaining objects – candidates for allocation – such ones, which would have type *A* relationships with *W* object. If yes, it becomes type V object and it is positioned possibly close to *W* object on the allocation plan. If there are several type V objects, we choose for arrangement one, which has the highest sum of total closeness rating TCR. If there are several such objects also, we pick one of our choosing. Next type V objects are being searched for. If there still are object having type A relationships with type W objects, the entire process is repeated. If there are no objects of such relationship, it is explored, whether type V objects have got type A relationships with the C objects, not allocated yet. If yes, such an object becomes type W object and it is situated on the allocation plan, whilst the C object, with which A had relationship, becomes candidate for allocation, so the V object. If neither of W and V objects do not have type A relationships with the C objects, the closeness rating is lowered by 1 to I, O, and the entire process repeats. Found object becomes of the W type and is situated on the allocation plan. Now type *V* object of *A* relationships is searched for it amongst type *C* objects and so forth.

As a result of the process several loose groups of objects are created, which are focused around objects of high total closeness rating sums.

9 Computer aided processes planning CAPP

Computer aided process planning *CAPP* is a crucial part of Computer Integrated Manufacturing [29]. The fundamental aim of research into *CAPP* systems is automation of work connected to development of technological process plans [30]. Those systems are supposed to be responsible for selection of appropriate machining operations and determination of their order, in order to produce a given part in technologically correct and economic manner [30], [31].

There is no common ground in terms of settlement over functions realised by *CAPP* systems. Basic functions of *CAPP* systems are [31]:

- identification of machining features,
- assignment of machining operations to every technological feature,
- determination of machining operations' order,
- elaboration of setup plans and determination of required fixtures,
- generation of NC codes for numerically controlled machine tools.

On the other hand the work [32] enumerates the following stages:

- analysis of part requirements,
- selection of raw workpiece,
- selection of manufacturing processes,
- selection of machine tools,
- selection of cutting tools,
- determination of machining conditions.

In the work [33] is given the following scope of tasks realised by *CAPP* systems:

- analysis of design documentation,
- determination of machining operations,
- selection of tools for execution of individual operations,
- elaboration of fixtures,
- determination of requirements of individual setups,
- selection of cutting tools,
- determination of machining operations' order,
- selection of machining parameters,
- development of *NC* programs,
- simulation of developed *NC* programs.

In the majority of cases, selection of machining technology is limited to machining. It follows from the fact, that this type of material removal process is still the most wide-spread and commonly used in the industry [34]. By analysing publications dedicated to *CAPP* systems one can observe, that utilisation of features for integration of generative systems with *CAD* systems is the dominant approach. According to some scientists, all currently developed generative *CAPP* systems use features [35].

Further stages of a CAPP system's operating, after features identification, include:

- determination of the type and order of machining operations,
- selection of machine tools, tools and fixtures,
- determination of machining parameters.

With the stage of determining demanded machining operations, is also related determination of their order. Two tasks constitute that stage. Firstly, technologically correct machining operations' order needs to be established, which is sometimes called the critical order of machining operations. Failing to keep that order can render impossible to achieve specified in documentation dimension and shape precision, or even prevent technological process from realisation. An example can be the necessity of machining datum surfaces prior to machining a part's elements, which use those surfaces, or machining of features nested in other features. The second optional stage is optimisation of operation order by maintaining beforehand established, critical sequence of operations. Those issues are going to be described in detail in further part of the work.

The effect of a generative CAPP system's operation should be documentation, including all necessary parameters of machining operations. The work on CAPP systems shows, that perhaps in the future, those systems will be capable of generating control programs for NC machine tools.

The very first CAPP system was created in 1976 [30]. Since then many work and research has gone into development of ever-finer solutions or focusing on chosen problems related to construction of those systems.

Amongst computer methods improving the work of technologist three major approaches are distinguished: variant, semi-generative and generative process planning – fig. 21.

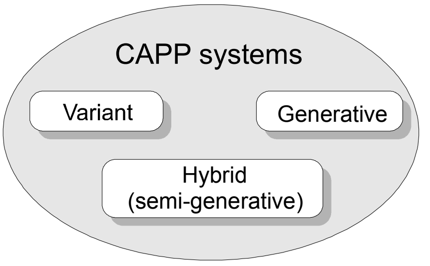

Fig. 21. Types of CAPP computer systems aiding technological process planning

The presented order reflects the chronological development of those systems, as well as the degree of advancement in the area of using computer technologies.

9.1 Variant method

Variant method of processes planning is characterised by high degree of similarity to the traditional – manual way of preparation of technological documentation. This method is based on distinction of group of parts displaying similarity and assigning to them standard technological processes. Technological documentation of new parts is created by introducing modifications to the standard process plan, elaborated for reference parts, similar to considered parts. Diagram of variant processes planning is presented in fig. 22.

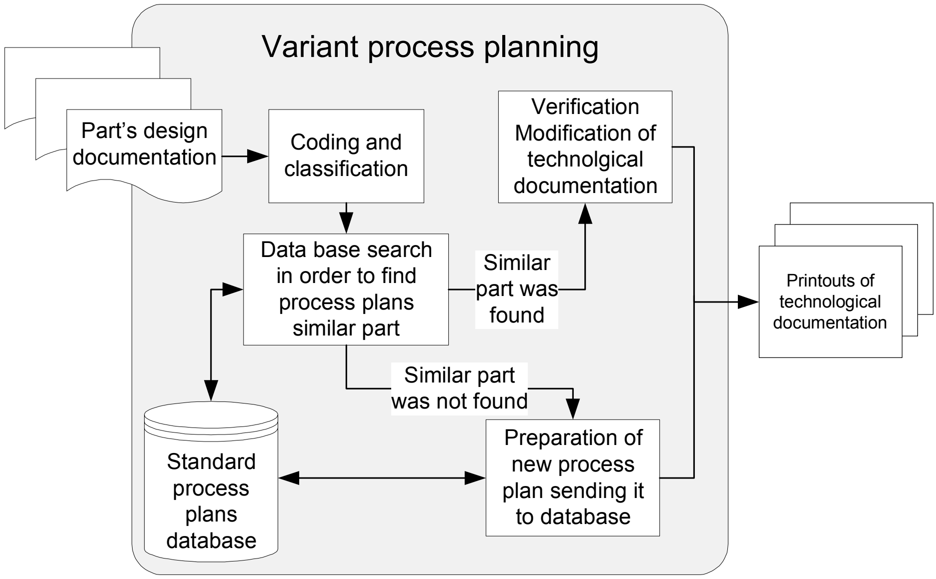

Fig. 22. Diagram of variant process planning

In order to improve the process of identifying technologically similar parts in variant CAPP systems were implemented rules of coding and classification of parts. This issue is known as aforementioned Group Technology notion.

Other issues connected with variant machining processes planning are [36]:

- development of database of standard machining processes;
- definition of rules of communication with the database and proceeding algorithms during searching through it in order to find standard process plans;
- establishment of way feedback information is flowing to the database, which contains processes plans;
- development of a module generating the final technological documentation.

An interesting approach to coding and grouping of machine parts is presented in the work [37]. The author had developed a method of digital representation of machine elements and a method of grouping parts in terms of design and technology utilising the neuron network. Two-layer network architecture of Kohonen type was built allowing for grouping parts of machines. Coding of machine elements had been performed on basis of characteristics of design and technological features, influencing selection of technologies. The digital representation of a part was obtained by development of a feature vector, including figure data characterising individual features of a given part [37].

The variant method of planning technological processes had been used in the **SYSKLASS** [38] integrated system. In that system identification of essential parameters of produced parts is realised through use of a classifier, based on hierarchical combination of part’s shape and parameters identification methods. Helpful in that operation are design features bases and element’s properties, and data connected to the manufacturing process. Variant manner of system operation manifests itself at the stage of developing manufacturing technologies, through the possibility of using technological information included in the known solutions base and previous results of technical production preparation [38].

Next example of a variant CAPP system, is computer system aiding process planning for shafts - **POLCAP** [39], [40]. That system, developed in Institute of Engineering Technology of Poznan University of Technology, characterises with modular structure. Elaboration of technology takes place in form of dialog with the computer. By means of it, were developed the structure of technological process and individual technological operations. Designing of process takes place on the basis of a typical technological process, with its possible variants, for a chosen item class – shafts.

Variant method of process planning in CAPP systems is characterised by many advantages. First and foremost it imposes systemisation of an enterprise's products through coding and classifying [41]. Introduction of databases to a great extent eliminates from a technologist's work activities not directly linked to taking technological decisions. It shortens the time of elaborating technological documentation through usage of standard plans, technological processes executed beforehand. Due to utilisation of that technological documentation, the probability of failure occurrence in the production phase falls on account of fact, that defined processes were already previously verified.

Presented method characterises however, with serious flaws. The most important one is the necessity of manual elaboration of technological documentation in case, when there is a need for developing manufacturing technology for a part, whose technological documentation was not placed before in the database of standard machining processes. Similarly in the case, when in enterprise's production system appears a new machine tool or possibility of performing new technological processes, the current technological process plans need to be manually verified and changes imposed by new manufacturing possibilities implemented. Above-mentioned inconveniences imply next serious drawback of the variant method in process planning - the necessity of employing a highly skilled technologist at the post of technological process planner. His knowledge and experience are key indicators of correct functioning of a variant CAPP system. In that case it may be noted, that computer technologies employed at variant process planning are only tools aiding the technologist's work, and the most important matters during elaboration of manufacturing technology he still examines himself [36].

9.2 Generative method

Bearing in mind inconveniences of variant method in CAPP systems the generative way of process planning had been developed. The essence of that method is creation of technological process plans for new products, without relying on previously developed technological processes [42], [43], [44] , [45], [46], [47], [48], [49], [50], [51]. The next important requirement set for generative CAPP systems is limitation of human input to most crucial, key technological decisions [52], [53]. Correctly operating generative CAPP system should use directly CAD design data, omitting the phase of design documentation interpretation by the technologist. Based on analysis of literature it was taken note of, that processing of CAD data for needs of process planning is realised through usage of one of three major methods: part designing through usage of features, recognition of features in the CAD model and languages of construction description (fig. 23).

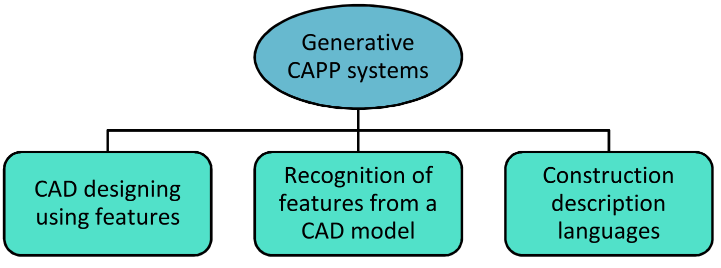

Fig. 23. Division of generative CAPP systems according to form of input CAD data

On account of the way of processing information there are generative CAPP systems distinguished, functioning on the basis of:

- artificial intelligence methods (expert systems, genetic algorithms, neural networks),

- databases with extensive DBMS management system (*Data Base Management Systems*) [54].

9.2.1 Features in generative process planning

Features are defined in many different ways, depending on in which area the term is used. The general definition of the term “feature” is:

“**Feature** represents, from engineering point of view, a set of parameters characterising properties of parts or assembly” [55].

Similar definition was formulated in the work [56]:

“**Feature** is a set of information about an item, including geometrical and technological characteristics, of different level of complexity and hierarchy, used during construction, designing of technological processes or other engineering work”

In the area of product design, features as geometric primitives, are used for ensuring functional demands of designed part [44]. Example: a rib is a design feature applied for increasing a part’s rigidity. An example of a part with highlighted design features is presented in fig. 24 [57].

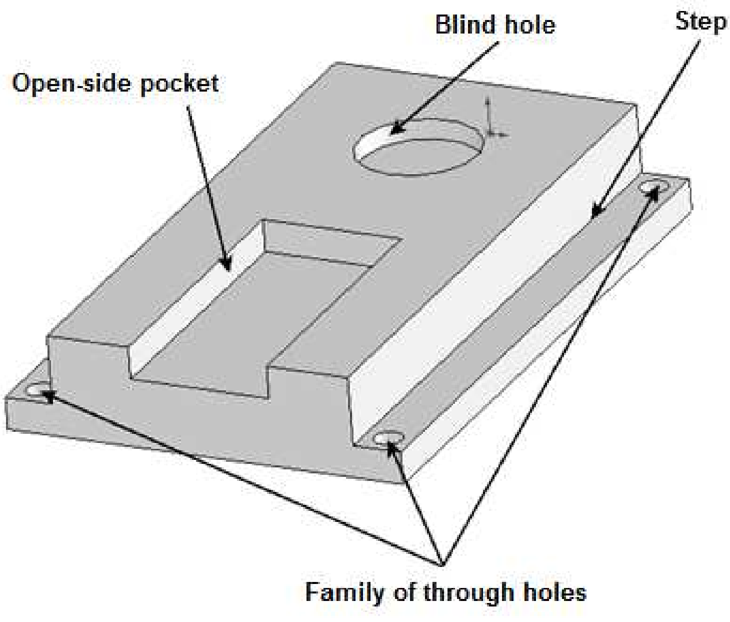

Fig. 24. A part with distinguished design features [57]

Features, from technological point of view, are surfaces or volumes obtained by operations removing material in production process [44]. Technological feature in form of a cylindrical through hole is manufactured by the operation of drilling, an object in form of a groove can be obtained by using the milling operation.

The other definition of technological features:

> "Technological features determine a set of correlated geometrical elements, which correspond to individual technological processes, or can be used for determining appropriate manufacturing methods in order to obtain demanded geometry of a part" [55].

The STEP norm (**ST**andard for **E**xchange of **P**roduct data) AP-224 of series ISO 10303 “Definition of mechanical products for planning processes by means of machining features” includes division of technological features into four types: machining, temporary, replicated and complex features (fig. 25).

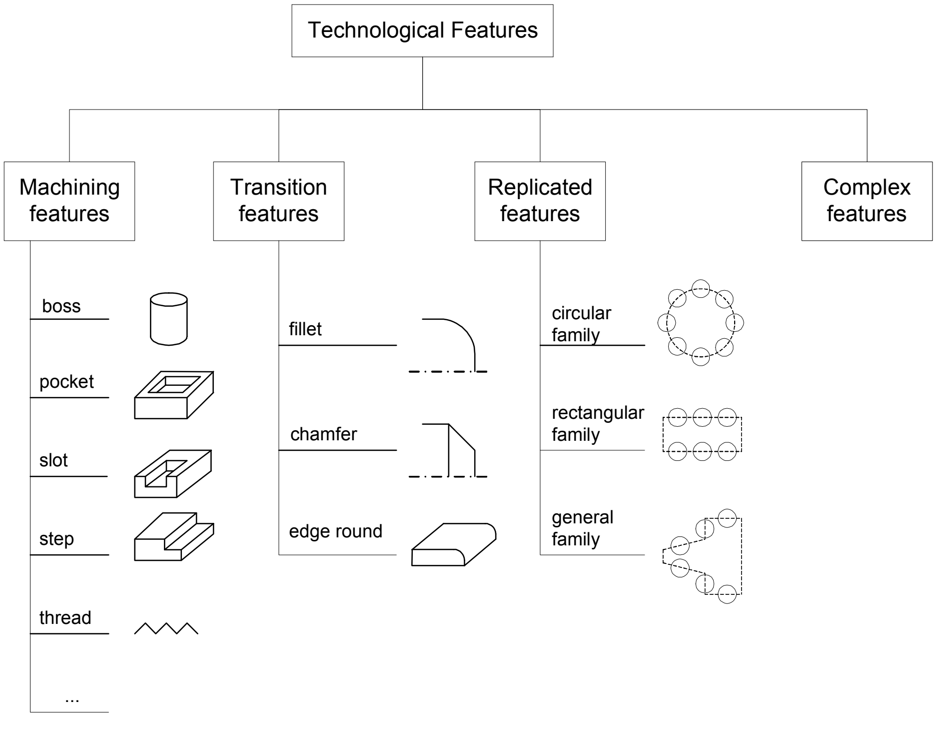

Fig. 25. Technological division of features according to STEP AP-224

An example of parts with distinguished technological features is presented in fig. 26.

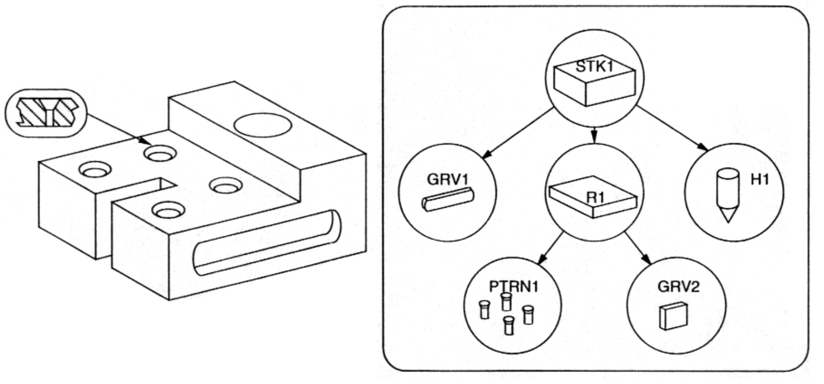

Fig. 26. Example of a part and extracted from it features [55]

9.2.2 Forward and backward process planning

The task of generative CAPP systems is to define a plan of technological processes determining the way of transforming the raw material into a finished product. There are two methods known of procedures for dealing with process designing:

- *forward planning*,
- *backward planning* [58], [36].

The square one in **forward** planning of processes is the initial state of the part processed in form of raw workpiece. Through determination of machining operations are removed consecutive technological features, in form of material volume, until obtainment of final form of processed part [36].

Backward method of planning processes is the reversal of the code of practice in relation to forward planning. The initial state of the item is its final form, enclosed in the design documentation. Next, intermediate state of the item is obtained through taking into account requirements of surface finishing precision and addition of operational machining allowance, which will be removed in successive machining operations. As an effect of those proceedings a rough shape of the raw workpiece is obtained. The final form of the raw workpiece is established by taking into account other factors than just the geometry of processed item e.g. volume of the production batch, or material properties of a given part.

Customarily the design documentation describes the product designed in the final form, exclusive of raw worpiece, this being the case, the forward method of planning processes has not found a wider application in practice. The difficulty of forward planning follows from the fact, that it is troublesome to determine the raw worpiece, which constitutes the starting form of item in the process planning method described.

In practice backward planning of technological processes is commonly used. Usage of that method for generation of intermediate states of processed items is presented in the work [58].

9.2.3 Obtainment of technological features

In backward planning, widespread are technological features (TF). They determine the most important information about the geometry of machined item, processed from design documentation for the need of preparing manufacturing technologies. Geometrical CAD design data during transformation into TF are enriched in additional information required by technologists, being e.g. detailed material data, special requirements about the surface quality after machining. During integration of CAD design environment with the area of planning manufacturing process CAPP, the process of obtaining TF from design data can be divided into two mainstreams [44], [59], [60], [61], [62], [63]:

- design by features,

- features recognition in CAD models.

General model of the process of obtaining machining features from design data orientated on design features is presented in fig. 27 [64].

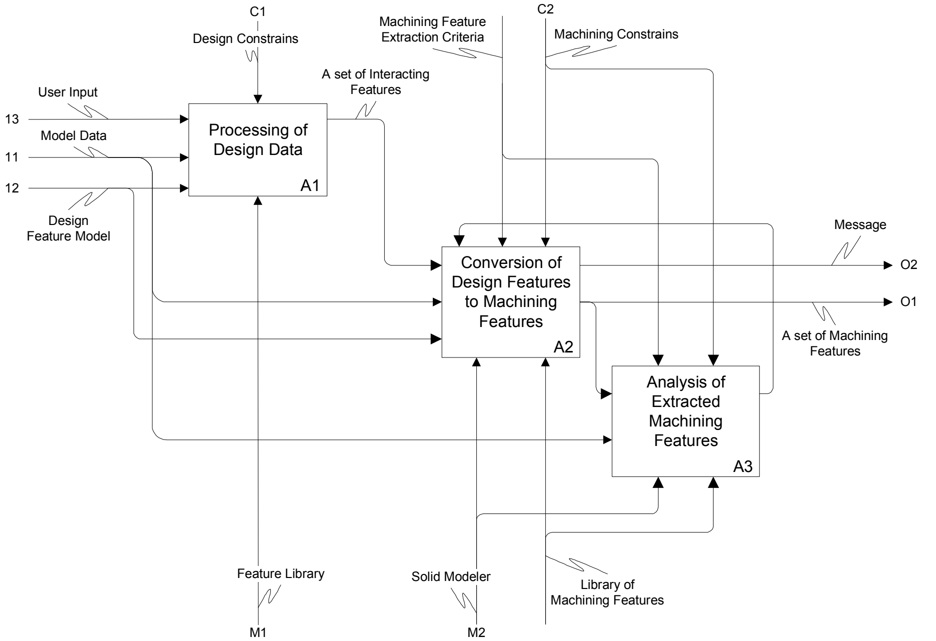

Fig. 27. Process of identifying machining features - IDEF0 model [64]

Distinction of technological features from design data, allows for commencing the second stage of elaborating the plan of technological processes, namely assignment of technological features to individual machining operations used for performing them. Apart from selection of types of machining processes, machine tools need to be selected, in which those processes will be realised, tools and instrumentation for individual operations need to be determined, as well as machining parameters need to be defined.

Aforementioned issues can be divided into two main groups:

- activities being easy to build algorithms realising them e.g.: selection of machining parameters, value of operational allowance;
- activities requiring technological knowledge e.g.: selection of machining type, determination of operations order.

In generative CAPP systems the first group of activities does not pose any major hardships during computer implementation. Using norms, alignment charts and other numeric data for processes planning allows for building algorithms for programs selecting numerical data of machining parameters based on information entered from aforementioned sources.

The second group of above-mentioned issues, requires application of decision logic, when solving certain problems. The most commonly used, in that area, methods of supporting the decisional process are: decision trees, expert systems, neural and semantic networks, genetic algorithms.

9.2.4 Expert systems in generative CAPP systems

The most widespread method aiding planning of technological decision processes are expert systems. Those systems constitute a part of branch of knowledge called artificial intelligence. The task of those systems - which are also called advisory systems – is proposing to the user certain variants of solutions for specified earlier problems, requiring undertaking a decision. The user may accept or reject the solution suggested. Correct functioning of expert system is possible only, when appropriate amount of knowledge from a given field – in the case being described – technological knowledge has been entered into the knowledge base. Unquestionable advantage of expert systems is the possibility of aggregating in them capacious technological knowledge in a systemised manner in form of: facts, production rules [65]. Such form of knowledge representation allows for accumulation of messages and data from different specialists from a manufacturing domain, enriching the functionality and capabilities of the expert system in terms of aiding decision process during preparation of technological documentation.

Usage of an expert system in the area of technical production preparation is presented in fig. 28 [66].

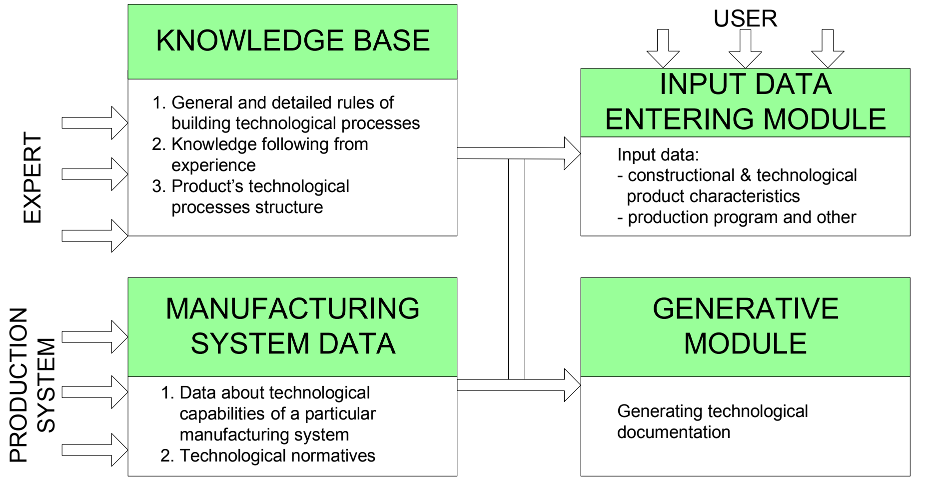

Fig. 28. Application of expert system in technical production preparation [66]

In presented way of using an expert system in the area of manufacturing technology preparation, production process designing is aided by means of entered data on the decision problem and analysis of technological capabilities of a particular manufacturing system. Solution of a concrete technological task depends on technological knowledge, implemented in the expert system, presented in form of detailed technological rules obtained from experts – technologists. User of the system enters input data, providing information necessary for module processing technological knowledge, what allows for generation of certain set of solutions of a particular task. Accepted solutions are stored in computer's memory, and results elaborated in form of technological documentation are used in the manufacturing process of a given production facility [66].

By analysing expert systems one can distinguish in them the following main modules fig. 29 [66]:

- ***knowledge base*** – contains representation of knowledge from a given domain, necessary in the process of solving decision problems;
- ***inference engine*** – it searches through rules implemented in the knowledge base and checks their applicability in particular cases of queries posed to the system;
- ***fixed database and variable database*** – those are sets of data, regarding a particular issue, systemised in a defined manner. Database of variable data is expanded during system's operation and contains user answers and indirect inferences found by the inference system;
- ***user-interface*** – allows for communication between the user and expert system. The way in which the module is organised depends on creativity of the person designing the system. It is often divided into two parts: entering of input data and information characterising the issue and generation of solution suggested by the system;
- ***knowledge acquisition module*** – allows for acquisition of knowledge from a given domain and recording it in the system knowledge base,

- ***explanation module*** – at a user's request the module presents justification for made by the system decisions through presentation of the reasoning's course.

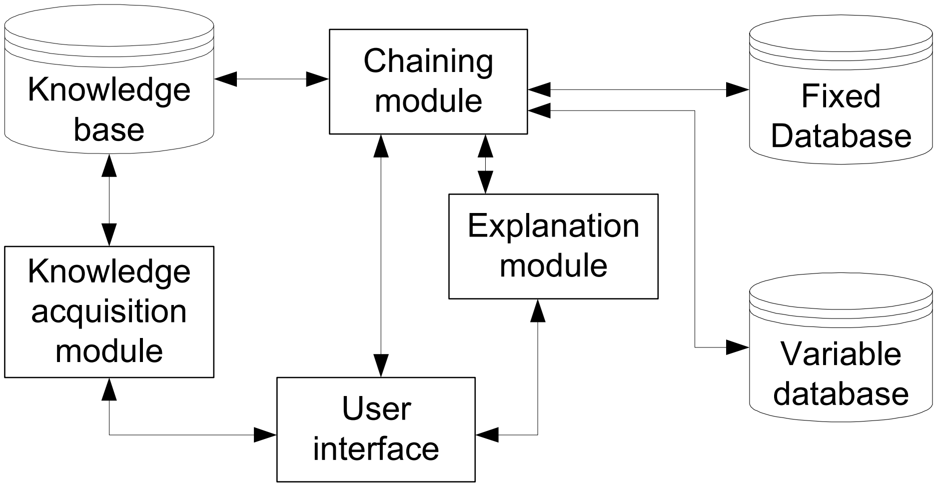

Fig. 29. *General structure of expert systems* [66]

Expert systems found wide application in the area of technical production preparation. Research into that field have been developed in professor Knosala's team in Institute of Machine Technology and Integrated Manufacturing Systems of Silesian University of Technology. In the work [67] is presented a prototype advisory system aiding technological processes designing of hydraulic cylinders' components. Knowledge representation method had been developed which allows for aggregation and processing of knowledge from the scope of designing technological processes of axisymmetric machines elements and corpuses of non-complex design. Structure of developed advisory system is presented in fig. 30 [67].

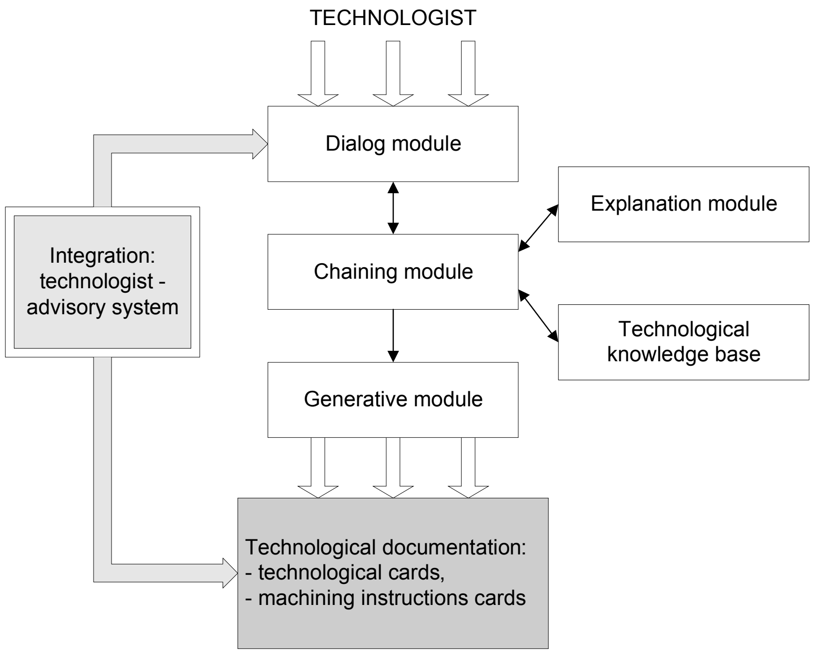

Fig. 30. *Structure of advisory system aiding technological process planning* [67]

Computer implementation of the developed methodology had been conducted based on shell expert system MAS and MS ACCESS database in MS Windows environment. Next example of expert system application in solving technological tasks is constituted by developed in Institute of Production Engineering and Automation of Wroclaw University of Technology, prototype expert system for designing the process of shaft machining [14]. The systems contains knowledge base in form of rules governing the process of selecting the form of a raw material, determining the type and order of operations necessary for producing the item and assigning machine tools and workplaces to individual operations. Other examples of expert system applications in technological processes planning are included in works: [31], [68], [32], [65], [69].

10 Features in technical production preparation

Fundamental definitions regarding features in the area of elaborating manufacturing processes were presented in the previous chapter. As aforementioned there are two fundamental types of features distinguished: design and technological. In hereof paper four types of features are distinguished: functional features, design, technological and machining features (fig. 31).

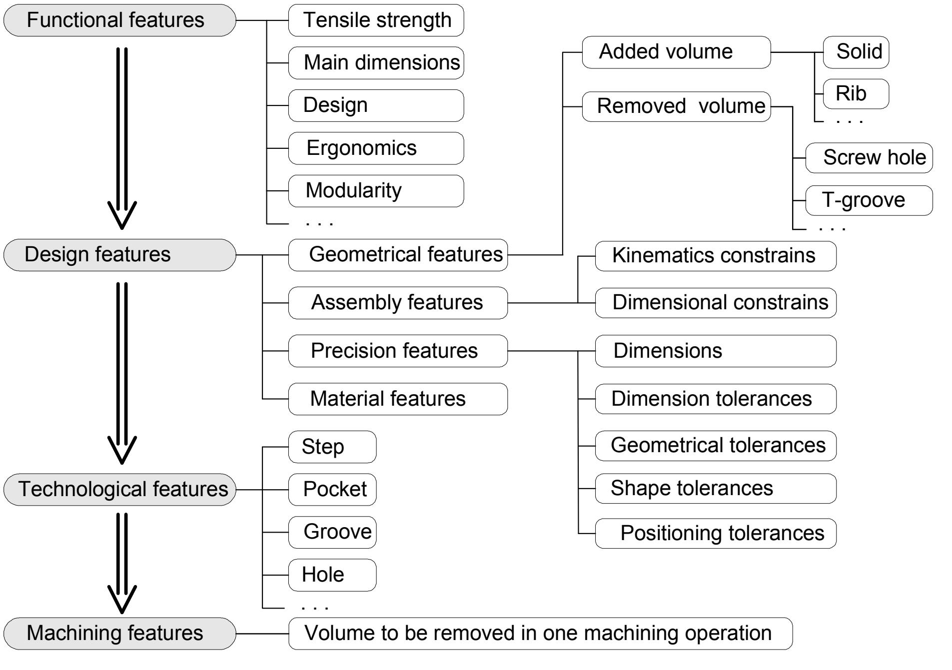

Fig. 31. *Features in production preparation*

The division is contingent on data character, included in individual types of objects. It takes into account parts' functional assumptions, geometry, material data and a set of design and technological data describing the geometry.

10.1 Functional features

Functional features contain information related to assumptions, which the finished product is supposed to fulfil. Part of that information can be presented in form of accurate figures, e.g. the possibility of loading a given product with force of 150 N, other information is conveyed in immeasurable form e.g. the product's shape needs to be ergonomic and stylistically contemporary. Examples of functional features for a car part are presented in the table 4.

Table 4 Functional feature example

Part number	**Part name**	**Functional features**
345.82.765.32	Gear shifter	1. Allowing for activation of gears with force of min. 0.5 [N].
		2. The shifter's manoeuvring space cannot collide with the other interior equipment [fig. 234.43.543].
		3. The shifter's aesthetics compliant with the style line
		4. Colour scheme fitting the interior.
		...

In a production enterprise the described functional features are handed over from the new product development division to design office. Designers analysing posed functional requirements design product geometry. Then strength analysis are made along with other, which are necessary for a given part being designed. After completion of those analyses the form of part's geometry is elaborated and the material approved, out of which the part is going to be produced. Already on that stage we can talk about parametric model of an item, which is represented by means of design objects.

10.2 Design features

Design designing of a new product is executed based on guidelines included in specification of functional features. In hereof paper there are four major groups of design features distinguished (fig. 30):

- geometric,
- assembly,
- precision,
- material,

The presented division is contingent on modern CAD systems' abilities. Geometry of part designed in such a system is modelled by using mentioned design features. For a complete description of design it is necessary, not only to build a part's geometry, but also to give exact parameters characterising that geometry, so: dimensions, tolerances, information on surface finish quality, deviation of position and shape, datums, material parameters, and in case of assemblies of parts – kinetic constraints between components. The process of modelling a part's geometry completed with features is depicted in fig. 32.

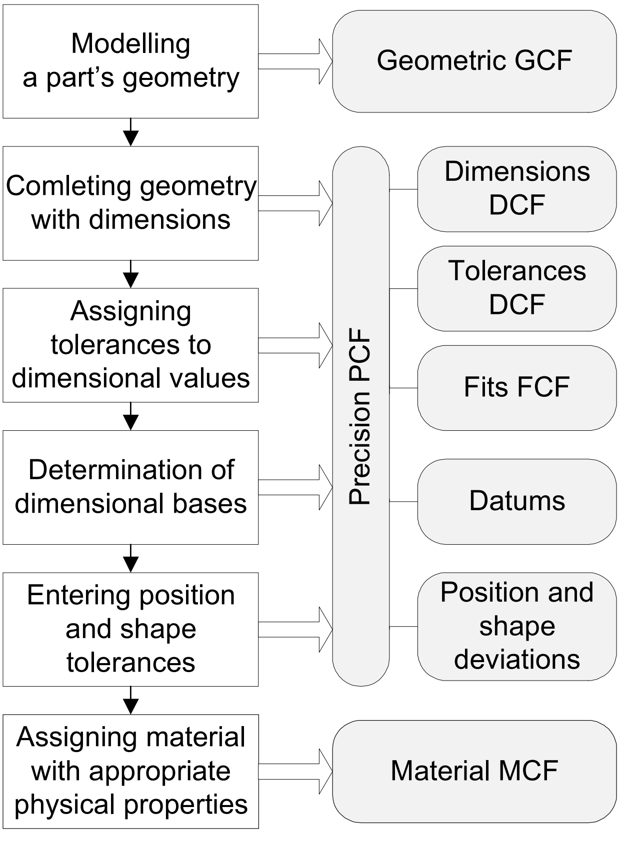

Fig. 32. *Process diagram of creating design features during designing in a CAD system*

Practical realisation of formulating design features is presented in fig. 33. Screenshots were made during successive stages of designing in the SoliWorks CAD system. Three main stages were distinguished:

- part's geometry modelling – design of geometric, design features,
- parameterisation of geometry through addition of dimensions, tolerances, fit inferences, position and shape deviations, dimensional bases, surface finish quality – precision design features;
- determination of raw material, design feature.

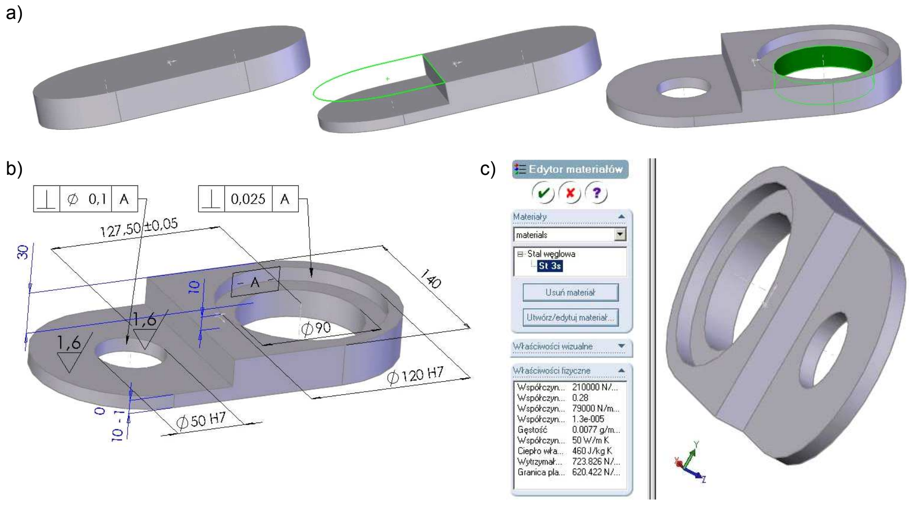

Fig. 33. Stages of creating design features: a) design of geometric features b) addition of precision features c) assigning material to geometry

In practice determination of material and final geometry of designed part takes place after having made necessary calculations (strength, stresses, displacements – calculated using FEM analysis , thermal, etc.).

The example presents features characteristic for single parts, it does not take into account assembly features, which are created in the processes of joining together components into an assembly.

Modern CAD systems operate on basis of parametric features. Similarly the designing philosophy in SolidWorks CAD system allows for designing through addition of successive geometry elements, entering dimensional values, tolerances, fit inferences etc. determining those geometric objects. Symptomatic of that system is storing information which has the structure of data related to computer model of designed part. Figure 34 presents main objects, out of which a part is constructed in the SolidWorks system. Distinguished here is the structure of dependencies between objects, those relations are of “parent – child type. In case of the system working in solid modelling mode for individual parts the highest level object is “part”. Other objects remain in dependency “child”, in relation to “part” object.

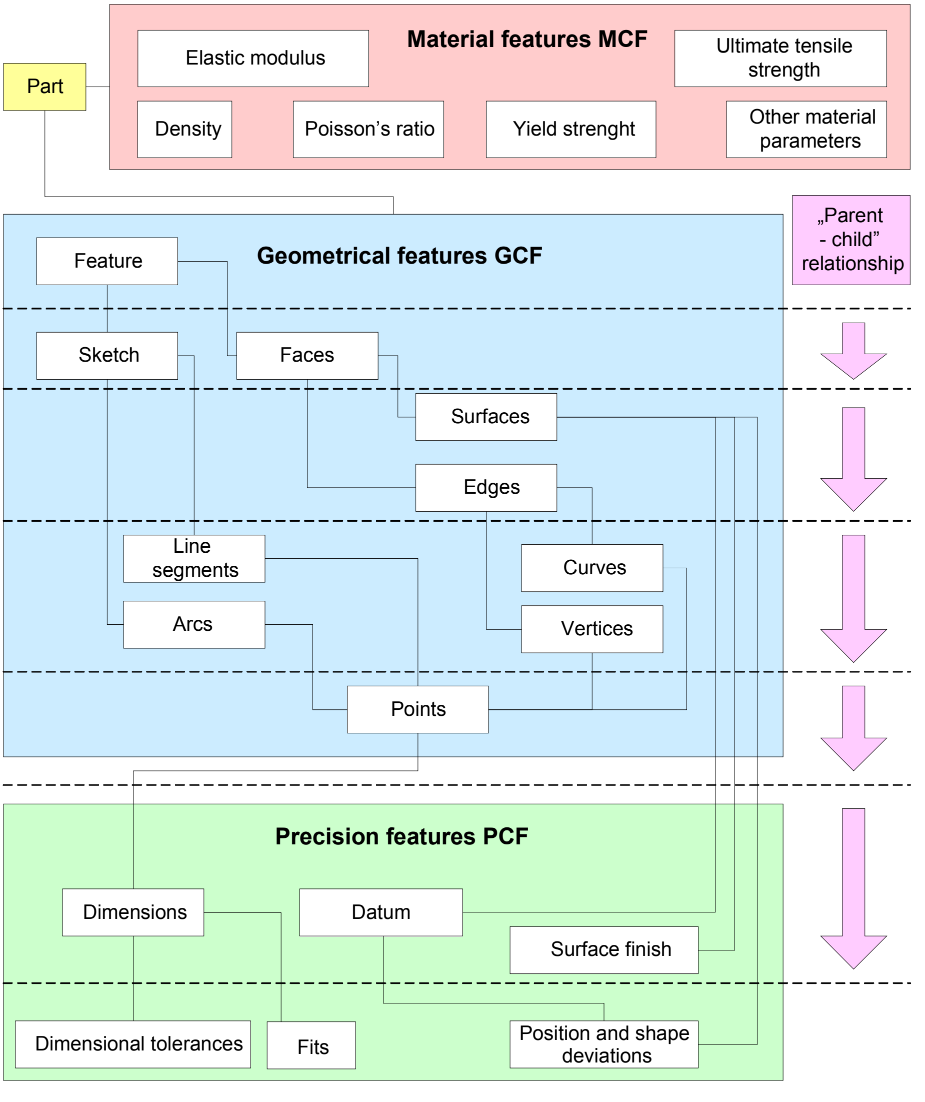

Fig. 34. Structure of given parts in the SolidWorks 2004 CAD system – divided into design features

Design process does not require entering all parameters of geometric features. Supplementation with precision and material parameters of geometric objects may take place in the subsequent designing stage. The data structure is updated on a current basis during modelling of individual stages of geometry along with precision features. Presented way of recording design features allows for flexible access to that information via Application Programming Interface – API.

10.3 Technological features

The result of designing in a CAD 3D system is computer geometry model of a part containing information both on geometry as well as parameters describing it. Direct utilisation in a CAPP system of design data in that form is impossible. Necessary becomes distinction of technological objects, having any significance in the process of developing manufacturing technology of a given product. There are different types of technological features. The division is contingent on used manufacturing technologies. Depending on the way of machining, technological features are divided into used in processing:

- material removal process (e.g. groove, pocket, hole, profile),
- plastic working (e.g. external contour, fold, overpress),
- casting (rounding, casting draft).

In material removal processes, technological features reflect volume of material being removed through technological operations. An example of a part with distinguished technological features used in material removal processes is presented in fig. 35. When analysing geometry of a part in order to specify technological features, different interpretations of features are possible. A cylindrical pocket from fig. 35, could have been interpreted as a special case of a shallow hole. The way a given geometry is attributed to particular types of technological features, depends on adopted assumptions defining given features. Differentiation of elements may be based on geometric data (number of arcs, mutual orientation of geometry elements), other criteria can be based on analysis of dimensions parameterising objects. Considering the aforementioned cylindrical pocket, the criterion deciding about the given geometry having been classified as a pocket, regarded numerical value, reflecting the ratio of diameter to thickness of feature.

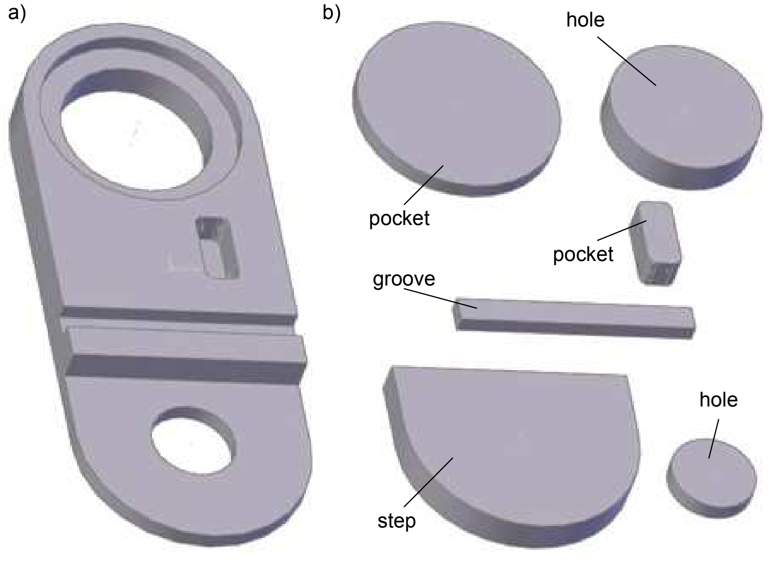

Fig. 35. *Examples of technological features in material removal process: a) part's geometric model b) technological features*

Due to lack of defined and systemised with precision types of technological features, as well as criteria deciding about affiliation of a given geometry with a particular group of objects, there are multiple divisions of TF, along with the way they are obtained.

Form of technological features in plastic working, is defined in a diverse range of ways in relation to material remove processes. Process characteristics of turning, overpressing, excision renders the technological feature as impossible to consider as volume of removed material. In the case discussed, the decisive role – differentiating individual cases – plays the character of plastic working processes. An example of a part with specified technological features in an element out of sheet metal is presented in fig. 36. That specific group of features requires separate definitions, as well as specific methods of identification in design geometry.

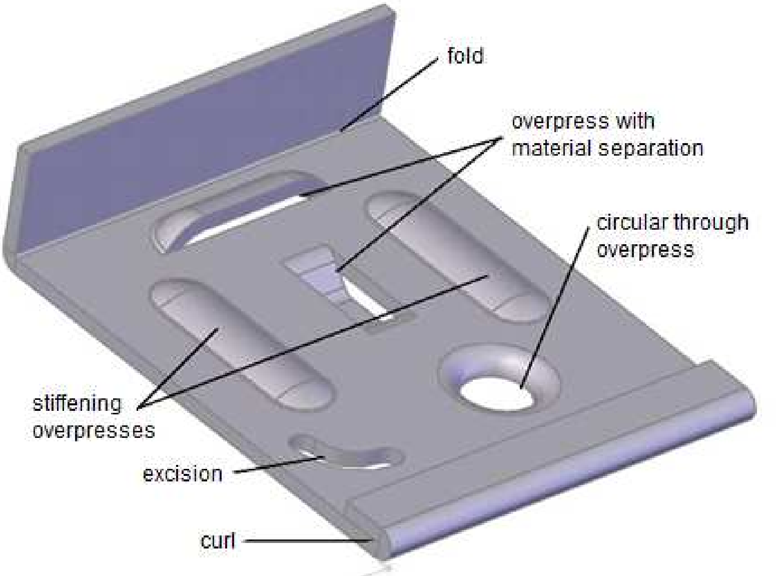

Fig. 36. *Technological features for a part out of a sheet metal*

Presented in detail characteristic of technological features in material removal processes does not exhaust however the subject of features. In case of other manufacturing technologies e.g. plastic working, casting, welding, features have got a completely different form.

10.4 Machining features

Technological features cannot constitute a straightforward set of parametric data for development of programs controlling NC machine tools' functioning. The reason for that is possibility of dividing the machining processes into roughing, semi-finishing and finishing. The division is dependent on precision demanded of end geometry, as well as on possibility of obtaining certain dimension and shape precision in individual machining operations. Only special cases of features can be obtained in a single machining operation – when the precision demanded after machining will be provided after one operation. In case of necessity of dividing technological process into more operations, for a given feature, it becomes broken down into a set of machining features. A machining feature reflects geometry removed in a single machining operation. Below drawing examples present the process of transforming design features into technological objects – a pocket, and that object in turn into a series of machining features. Figure 37 presents a CAD 3D model, containing design features in form of added material volume – rectangular cuboid, and removal of material fragment – the pocket.

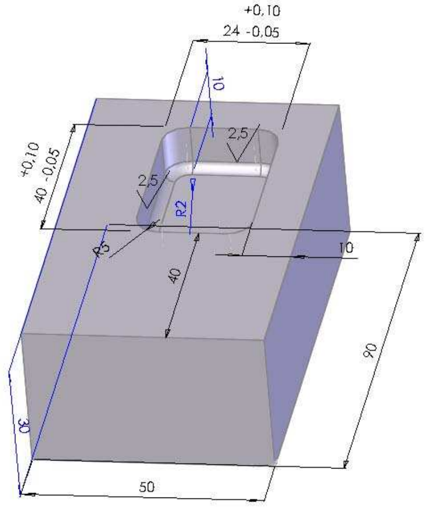

Fig. 37. Starting CAD 3D model for the procedure of distinguishing machining features

Geometric features from fig. 35 are parameterised by precision objects, in form of dimensions, tolerances, surface roughness denotations. After analysis of the design model, there was a technological feature identified within it in form of a pocket with rounded edges and a bottom. Parameterised form of that pocket is presented in fig. 38 a). Consecutive stages of creating machining features are contingent on adopted way of machining. Examples of machining objects presented in fig. 38 b), c), d), e), f) were created with following assumptions adopted:

- the pocket will be manufactured by milling machining,
- first machining operation is hole drilling, enabling insertion of end mill into material,
- subsequent milling operation removes the conical bottom left after drilling operation,
- milling was split into 3 stages: rouging, semi-finishing and finishing.

Presented way of technological feature decomposition into a set of machining objects allows for their full parameterisation. Dimensions characterising individual machining objects are entered bearing in mind inter-operational allowances resulting from prepared machining process.

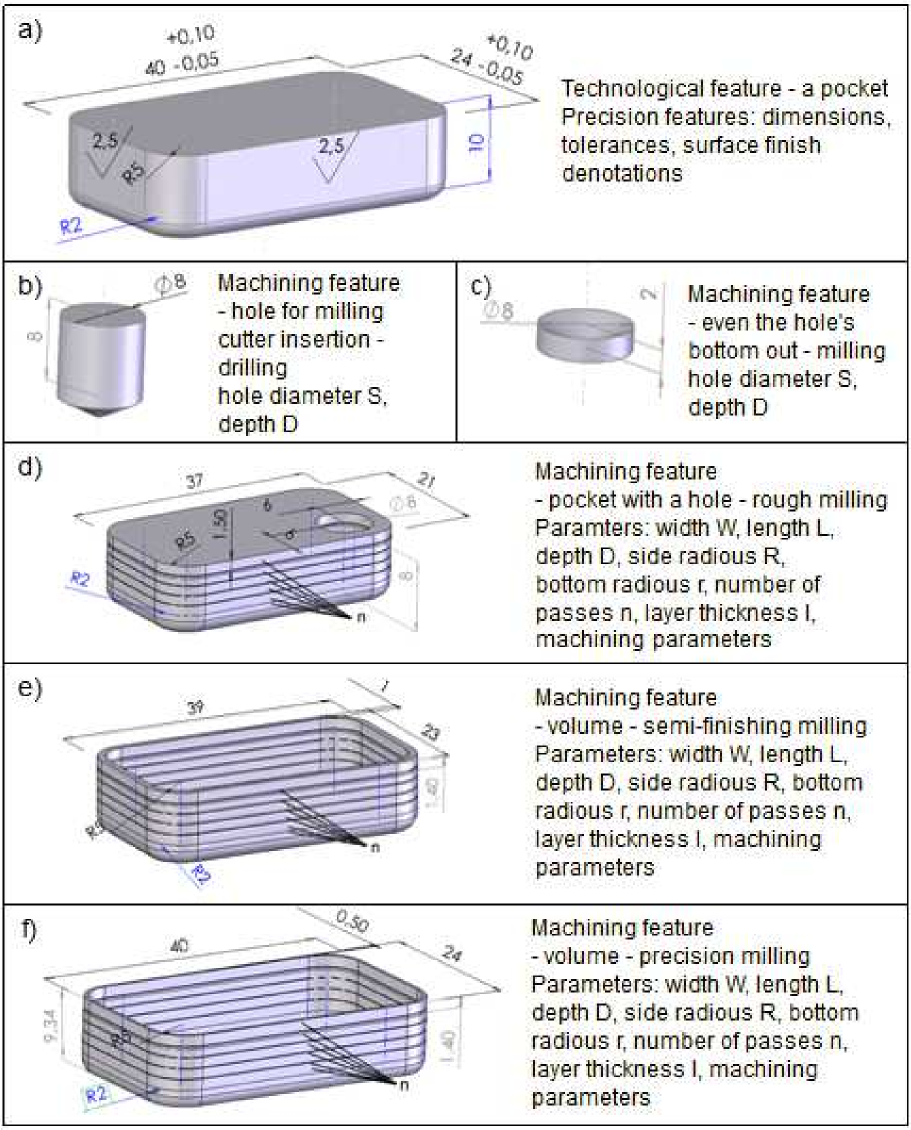

Fig. 38. *Stages of formation machining features: a) technological feature – a pocket, b), c), d), e), f) successive machining features of the technological process*

The method allows for generation of multiple diverse machining features, for a single technological object. The common feature shared by different divisions into machining objects is the fact that always the sum of elementary volumes of machining objects has to be equal to volume of technological feature.

10.5 Methods of obtaining technological features

There are distinguished the following ways of obtaining technological features, from design data describing designed product (fig. 39) [70], [64], [71], [72], [73], [74], [75], [60], [76], [77], [78], [79].

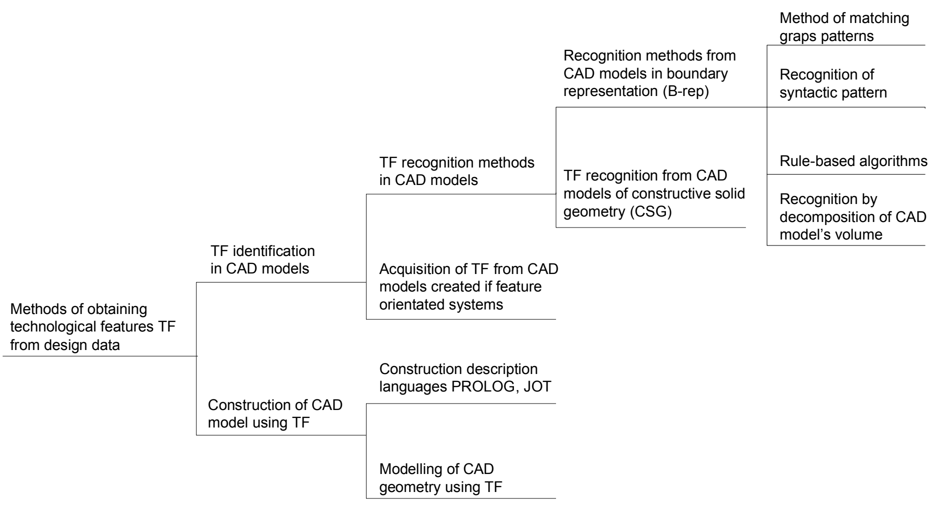

Fig. 39. *Methods of obtaining technological features from design data*

There are two main groups of methods for obtaining features:

- recognition of features on basis of CAD data,
- designing a part's geometry with use of features.

The most solutions have been developed in group of feature identification methods in CAD models. Individual approaches are related to the way of representing geometry in CAD computer systems: boundary representation, Constructive Solid Geometry CSG.

10.5.1 Languages of describing construction form

Designing an item's geometry with use of techniques, allowing for direct usage of geometric data in the process of developing technology, is a troublesome activity, because of imposing on the constructor specific instructions regarding designing. Such requirements are posed before the constructor – in methods of describing an item's geometry – by languages of construction description.

Examples of such languages are:

- JOT – developed in Institute of Technological Engineering and Production Automation of Cracow University of Technology under the direction of prof. A. Samek,
- PROLOG (fr. PROgrammation en LOGique) – programming in logic – high level programming language based on logic.

The JOT language uses the method of obtaining an item's geometry through revolution about the axis or contour extrusion along so-called "driving curve". The principle of building a part's geometry is depicted by fig. 40 [56]. During definition of contours, it is possible to define parameters necessary for development of technological process plans such as: roughness, hardness, shape and position deviations.

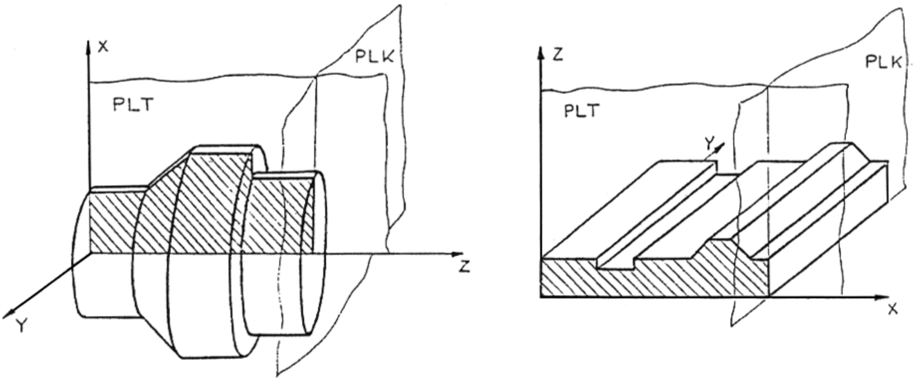

Fig. 40. *The idea of modelling a part's geometry in the JOT language* [56]

Usage of the PROLOG language in the scope of elaborating a set of design data for needs of manufacturing technology planning is concentrating on definition of features in that language, which are used for describing designed parts. An example of representation of features in the PROLOG language in presented in fig. 41 [80].

```
DRAWING(ID(CAD,DEMO1,PART),VUNO( 0),ELNAME( 1619),                        → circle or arc
 CDT3DC(CENTER( 4.49997330 , 0.502999902 , −0.31999993 ),
        END1( 4.43887520 , 1.04959488 , −0.319999933 ),
        END2( 4.06260300 , 0.836477220 , −0.319999933 ),
        BEGIN_ANGLE( 1.57079506 ),
        END_ANGLE( 2.37884712 ),
        MAJOR_RADIUS( 0.549999535 ),
        MINOR_RADIUS( 0.549999535 ),
        VECTOR1( 0.546595573 , 0.0610975623 , 0.0 ),
        VECTOR2( −0.0610974990 , 0.546595037 , 0.0 ),
        LINE_TYPE( 0),COLOR( 0))).

DRAWING(ID(CAD ,DEMO1,PART ),VUNO( 0),ELNAME( 1619),
        ATTRIB(NUMATT( 58),ATS( 0, 1, 0,
            0, 0, 0, 0, 0, 0, 0,
            0, 0, 0, 0, 0, 0, 0, 0))).

DRAWING(ID(CAD ,DEMO1 ,PART ),
        VUNO( 0),ELNAME( 1619),GROUPNAME( 1)).

DRAWING(ID(CAD ,DEMO1 ,PART ),VUNO( 0),ELNAME( 2609),                    → line
 CDT3DL(END1( 4.49997044 , −0.346997261 , 0.0 ),
        END2( 4.49997234 , −0.0470002294 , 0.0 ),
        LINE_TYPE( 0),COLOR( 0) )).

DRAWING(ID(CAD ,DEMO1, PART ),VUNO( 0),ELNAME(2609),
        ATTRIB(NUMATT( 177),ATS( 0, 0, 0,
            0, 0, 0, 0, 0, 0, 0,
            0, 0, 0, 0, 0, 0, 0, 0))).

DRAWING(ID(CAD ,DEMO1 ,PART ),                                            → planar surface
        VUNO( 0),GROUPNAME( 1),
        ATTRIB(NUMATT( 1),ATS( 0, 0, 1, 0,
            0.0 , 0.0 , 0.0 ,
            0.0 , 0.0 , 0.0 ,
            0.0 , 0.0 , 0.0 ,
            0.0 , −0.319999933, , −1.00000000 ,
            0.0 , 0.0 ))).

DRAWING(ID(CAD ,DEMO1 ,PART ),
        VUNO( 0),ELNAME( 1619),GROUPNAME( 22).

DRAWING(ID(CAD ,DEMO1 ,PART ),                                            → cylinrical surface
        VUNO( 0),GROUPNAME( 22),
        ATTRIB(NUMATT( 22),ATS( 0, 1, 23, 0,
            0.0 , 0.0 , 0.0 ,
            0.0 , 0.0 , 0.0
            0.0 , 0.549999893 , −0.319999933 ,
            0.502999902 , 4.49997330 , −1.00000000 ,
            0.0 , 0.0 ))).
```

Fig. 41. *An example of features' representation in the PROLOG language* [80]

Enumerated methods of building geometric models are conducive to direct implementation of design data into systems aiding technological process planning. Troublesome however is the process of recording a part's design in itself, and also the limited freedom of designing geometrically complex items.

10.5.2 Designing by features

Along with development of CAD systems, parametric systems have appeared, based on predefined geometric shapes – features, used in the process of designing a part's model. It was noticed, that one can enter into a

CAD system geometric primitives in form of technological features. Such objects can be used for designing geometry, and subsequently in systems aiding technological process planning – CAPP. An exemplary library of features is presented in fig. 42.

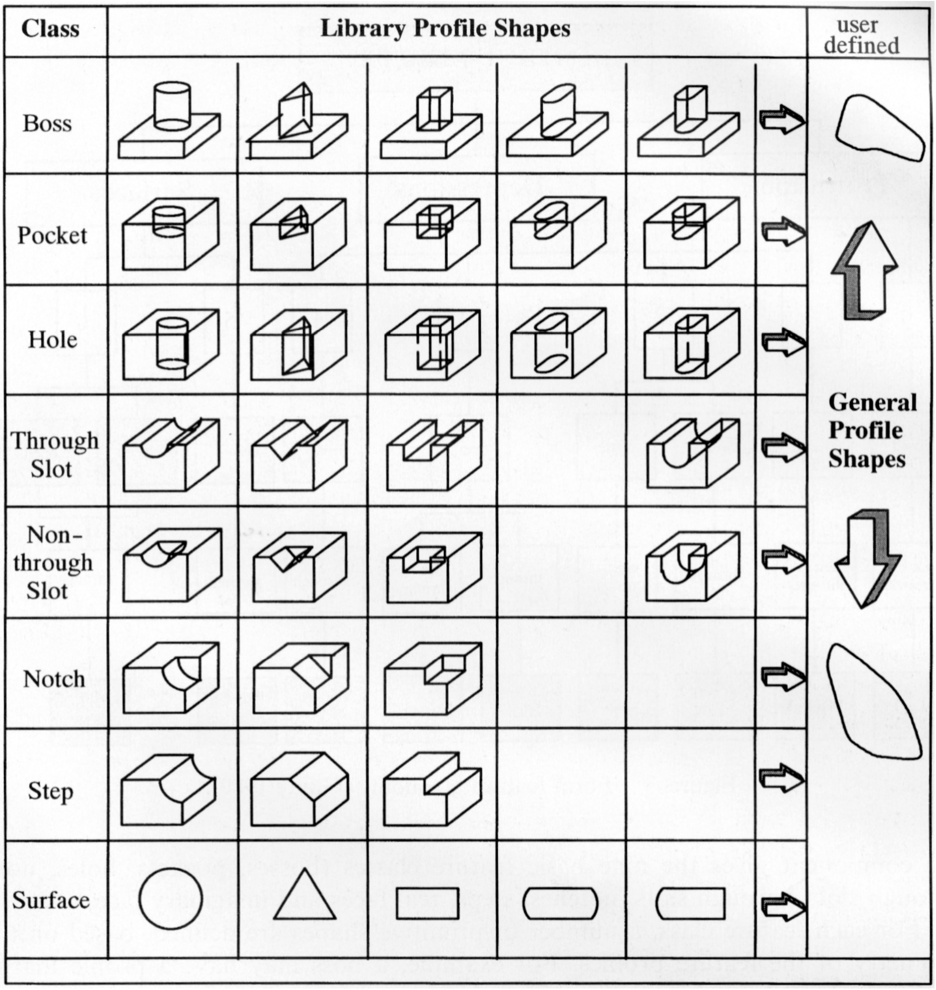

Fig. 42. *Library of features in a CAD system* [81]

Library of features was used in a prototype CAD system, based on core of ACIS solid modelling [81]. The system allows for designing geometry by:

- inserting features from the library,
- assigning values to object parameters,
- revolving,
- extruding,
- adding tolerances,
- defining dependencies parent – child,
- building complex features.

An item's geometry represented in that way, with use of features, can serve as a set of input data to a CAPP system. Shortcoming of presented method of obtaining features is the limited number of features saved in the library, available in the process of modelling geometry. Possibility of adding own features had been permitted, although in case of using that data in a CAPP system, entered objects are not going to be identified at the stage of process planning due to lack of information about standards for recognition.

10.5.3 AAG graph methods (*Attributed Adjacency Graph*)

Recognition of features, reliant on AAG graph analysis is based on an item's geometry saved in boundary representation B-Rep. Geometry saved in that way is converted into an AAG graph. Surfaces of a CAD model are reflected in form of graph nodes, connections between nodes have got attributes assigned and they reproduce geometry edges [82], [83], [84], [85].

Dependencies between adjacent surfaces are presented in relation to the edge, which demarcates them. If neighbouring surfaces create a concave angle, the edge has a value assigned to it of “1”, and if convex then the value of “0”. An example of geometry representation in form of an AAG graph is presented in fig. 43 – a).

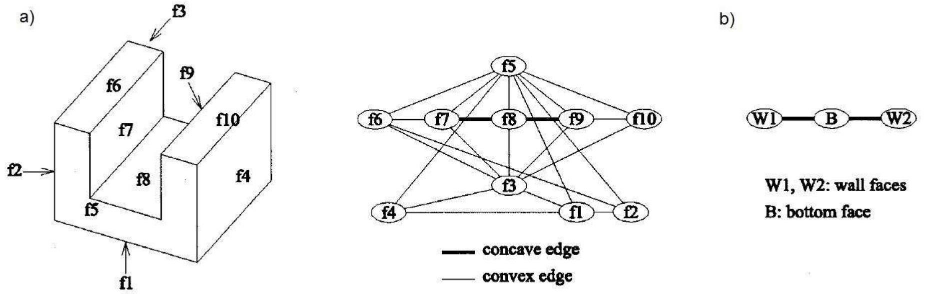

Fig. 43. *Recognition of features using AAG graphs a) a part’s geometry and its representation by means of Attributed Adjacency Graph b) a graph’s template representing a through groove* [82]

Recognition of features commences with distinction of vertexes, linked exclusively with edges with the 1 attribute. The procedure divides the graph into series of disconnected subgraphs, representing separate technological objects. Graph’s fragment with saved template representing the through groove is presented in fig. 41 – b). In a similar way one can save, and subsequently identify other technological features. The method presented is effective for a defined standard of features. It allows for a quick and efficient way of identifying the geometry of prismatic features from CAD 3D models. Its important drawback is the lack of possibility of identifying numeric parameters characterising a given feature.

10.5.4 Syntactic pattern recognition

Identification of features using the method of syntactic pattern recognition, means assignment of syntactic symbol set to a part's consecutive geometry elements. Such practice allows for identification of specified earlier patterns of syntactic description, characteristic for given features [86], [87]. In order to correctly assign a set of symbols, necessary is the knowledge of symbols description grammar characteristic for a given way of identification. Fig 42 a) depicts representation of symbols possible to use in the process of syntactic parts description as well as during defining syntactic patterns of features. An example of specified feature patterns in form of a hole is presented in fig. 44 b). Presented representation allows to a limited extent for representing complex shapes of features. It is realised through definition of syntactic symbols conveying information not only about the direction, but also having a unitary length. Hence there are, in the syntactic description of features, successively repeating symbols e.g. "cccc", denoting apart from the direction consistent with "c", its quad length.

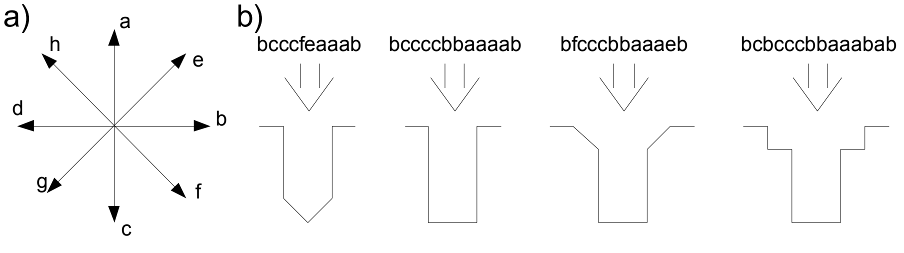

Fig. 44. *Syntactic pattern recognition a) grammar of syntactic symbols, b) description syntactic features patterns*

Syntactic pattern recognition can be used not only for identification of individual features, but also for decoding geometries of entire parts. Such practice has its application in the process of coding and decoding in Group

Technology. An application example of syntactic pattern recognition for elements out of a sheet metal is presented in fig. 45 [88].

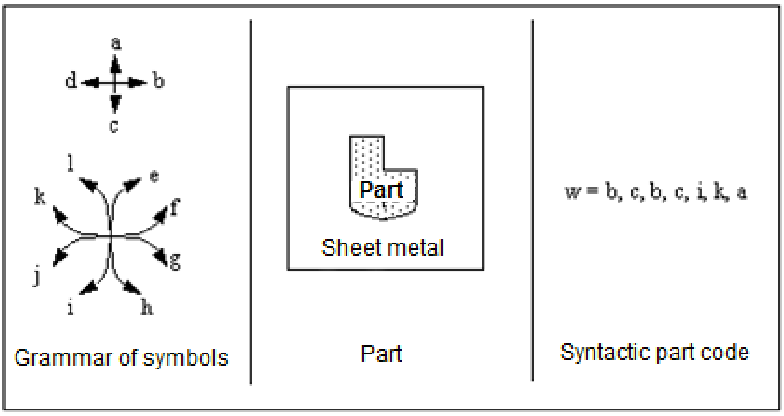

Fig. 45. *Representation of syntactic pattern for a part out of a sheet metal* [88]

The method of feature identification based on syntactic pattern has got a limited application due to the representation of planar geometry – 2D. Reading of dimensional parameters is ambiguous. There is an inability of transferring information holding technological characteristics describing a part's geometry.

10.5.5 Rule-based algorithms – logic approach

In rule-based methods, features are identified with use of rules constructed in form of conditions and conclusions: if – then – else clauses. Individual rules represent patterns of particular features [87], [88], [89]. During the analysis of a part's geometry, usually in form of boundary representation B-Rep, the correctness of conformity of rules' conditions is verified. If all conditions, for a given feature, are satisfied, it becomes identified within the system. In work [89] are presented exemplary rules defined for the process of groove identification:

> "Find Linear Slot Rule
> SEARCH During Hint Cycle for:
> A planar, nonstock face of the
> A second planar, nonstock face
> Delta Volume
> of the Delta Volume,
> not equal to, but parallel
> and opposing to the first
> face
> NOT(A previously created linear
> slot using these two faces)
> THEN
> Extend feature in all directions
> Search for slot floors
> Classify feature along, and
> perpendicular to,
> the sweep directions
> Evaluate classification for partial verification" [89]

In described method of feature identification, for processing rules describing features often expert systems had been used. Due to the character of processed information, it is difficult to write rules for features having common parts.

10.5.6 Recognition from neutral format of STEP data exchange

STEP data exchange standard, defined in the international ISO 10303 norm, contains information about a part's geometry, along with technological data. The possibility of using that standard for identification of technological features had been noticed.

A detailed description of mechanical data for technological process planning is included in the AP 224 application protocol. It contains necessary information for developing the technology of manufacturing a given part (material data, part's geometry, dimensions and tolerances, notes characterising specification and administrative information). Figure 46 presents a fragment of STEP AP 224 file containing previously-mentioned product data.

```
#38 = PRODUCT_DEFINITION_SHAPE('product shape','shape for product',#37);
⋮
#1690 = MANIFOLD_SOLID_BREP('',#1700);
#1700 = CLOSED_SHELL('',(#1710,#2080,#2450,#2540,#2620,#2700,#2770,#2860,
#2940,#3020));
#1710 = ADVANCED_FACE('',(#1720,#1900),#470,.T.);
#1720 = FACE_OUTER_BOUND('',#1730,.F.);
#1730 = EDGE_LOOP('',(#1790,#1830,#1870,#1890));
#1740 = EDGE_CURVE('edge_0',#1750,#1770,#520,.T.);
#1750 = VERTEX_POINT('vertex_0',#1760);
#1760 = CARTESIAN_POINT('',(0.,0.,0.));
⋮
#3090 = ADVANCED_BREP_SHAPE_REPRESENTATION('',(#1690),#460);
#3100 = ROUND_HOLE('','',#38,.T.);
#3110 = PRODUCT_DEFINITION_SHAPE('','',#3100);
#3120 = CARTESIAN_POINT('',(0.0,15.0,0.0));
#3130 = DIRECTION('',(0.0,0.0,1.0));
#3140 = DIRECTION('',(1.0,0.0,0.0));
#3150 = AXIS2_PLACEMENT_3D('',#3120,#3130,#3140);
#3160 = SHAPE_REPRESENTATION('',(#1050,#1070,#1080,##2000),#29);
#3170 = SHAPE_DEFINITION_REPRESENTATION('',#3110,#3160);
⋮
#3300 = HOLE_BOTTOM('bottom condition','flat',#3280,.F.);
#3310 = DESCRIPTIVE_REPRESENTATION_ITEM('blind bottom orientation','hole end');
#3320 = SHAPE_REPRESENTATION_WITH_PARAMETERS('',(#3310),#29);
#3330 = PRODUCT_DEFINITION_SHAPE('','',#3300);
#3340 = SHAPE_DEFINITION_RELATIONSHIP('',#3330,#3320);
⋮
```

Fig. 46. STEP AP 224 file sample [90]

Data from the file in STEP format constitutes input data in the process of feature identification. Figure 47 presents the process of features recognition in a STEP file.

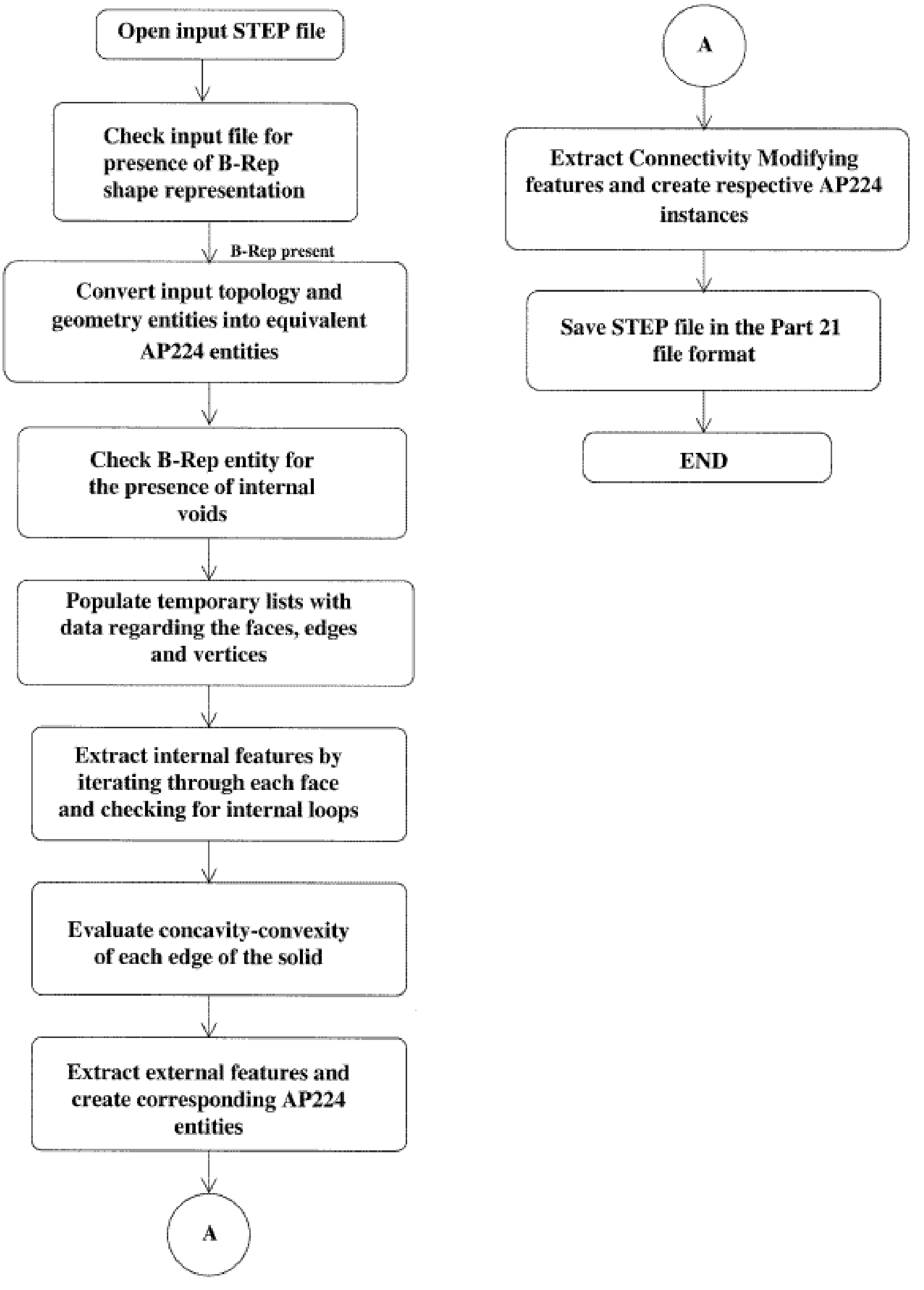

Fig. 47. *Diagram of features recognition based on data from a STEP file* [90]

After loading the STEP file, saved in AP 202 application protocol verification takes place, whether the file contains data describing geometry in boundary representation. If the file does not contain data about geometry, there is no topological information either, which is necessary in the process of features identification. In that case the system stops operating, informing the user, that a given file cannot be further analysed. If information about geometry is correctly saved in input file, the process is initiated of conversing geometry and topology of parts from the AP 202 format into objects characteristic for AP 224. Then the process of features recognition from geometric and topologic data in AP 224 format starts.

After recognition of features, the data is saved in "Part 21" format, which can be loaded by different CAD systems, or constitute the format of input data for CAPP systems, in order to develop manufacturing technology of a given part [90].

Presented method of features recognition from data saved in the STEP format, characterises with an unquestionable advantage due to the fact of using formalised data exchange standard. Problematic however is representation of data characterising individual features, because the STEP norm is still being supplemented with new application protocols and so far not all its modules have been developed yet.

Discussed methods of features recognition constitute only a part out of many, which have been developed within the confines of research. Along with development of computer techniques aiding designing, the methods based on construction description languages and syntactic representation are currently loosing importance. The majority of nowadays developed recognition methods are based on an item's geometry saved in form of a CAD 3D model.

11 Knowledge representation methods used in CAPP

There are three methods of knowledge representation, which derive from theories describing information processing by humans:

- semantic networks,
- rules,
- frames.

The last two methods of knowledge representation allow for building expert systems. Most commonly and the longest used, has been the rule representation. By means of rules one can record knowledge regarding solutions of fundamental problems related to technological planning, especially:

- recognition of technological features,
- assignment of machining operations to individual TF,
- determination of TF machining order.

Alongside rule representation, the second most popular is frame representation, referring to mechanisms of processing knowledge by humans, which is described in the following subsection.

11.1 Frame representation

The fundamental element of data structure in frame representation is a so-called frame. The frame represents notions, situations and concepts. The author of frame concept - Minsky [91] claims, that when a human encounters a new situation, he recalls from memory the structure called a frame. Frame is a memorised structure, whose some elements can be modified in need, in order to adopt it to reality description. Frame stores information in so-called slots. A slot is constructed similarly to a structure in *C/C++* language or to a record in *Pascal* language. In general, the frame representation resembles object representation, which can be treated as a computer implementation of frame representation [92]. Similarly as in object representation, also in systems using frame representation the notion of class and class intention is introduced. Hence there are frames being classes i.e. certain patterns describing a given object or notion, which have required for the description slots adopting particular values and frames being class instances describing a specified object or notion. With the notion of class is connected inheritance, facilitating definition of classes having usually all slots and facets of another class or classes. Individual slots are storing information of a particular type, likewise the variables in procedural languages do. Slots can also store sets of rules or procedures used for determination of a slot's value. A special case of a slot is a slot indicating to a frame. By means of such slots one can build a hierarchical structure. Moreover, slots can have default values, so the ones which are assigned to them once a certain frame is created (it can be compared to declaration with simultaneous variables initialisation in procedural programming languages). Additionally, the very same slot can belong to an excess of one frame and this is a fundamental difference compared to object paradigm. Properties of slots can be additionally described by means of so-called facets. Facets can i.a. impose restrictions on acceptable slot values, they can be used for obtaining values of slots or inform the inference mechanism how to process a particular slot. Typical examples of facets are those called in particular situations such as: slot's value change (*is-changed)* and request of using a slot's value – *(is-needed)*. The *Is-needed* facet is used in the situation when a slot's value is required to solve a problem, and its value is not determined.

In general, problem solving in expert systems using frame representation takes place in principle through calling methods attached to slots, what differentiates them from rule-based systems, which use for that purpose the inference engine and rules.

11.2 Rule representation

Rule representation is one of the most popular and the oldest methods of knowledge representation used for building expert systems [31]. In the sixties of the XX century it was proved, that in the majority of cases, the human reasoning can be presented by means of rules [93]. In the rule paradigm, rules represent heuristics, or so-called *rules of thumb*, which determine the set of actions performed in a certain situation. The elementary rule is composed of two parts:

- conditional part, containing list of conditions (premises),
- consequent part, containing list of conclusions.

Hence the basic rule can be written as [94]:

if *premise* ***then*** *conclusion*

Conditions describe a situation – state of object traits, which render the rule feasible. Generally, rules refer to long-term memory and describe dependencies which do not change over a short time span. Individual conditions are linked with logic operators, determining combinations of values of individual attributes, for which the rule is feasible. In turn the knowledge representing the short-term memory – current parameters of an analysed object or problem – is represented by means of facts. Facts usually adopt a form of trio <object, attribute, value>, or due <attribute, value>. In practical realisations of expert systems, facts resemble initiated variables – they have values of a particular type. On the other hand, the premises of rules do not have to refer to a single value, but they can define intervals of values for which the rule is feasible (in case of numeric facts). The effect following from a rule's execution is occurrence of a new fact or facts in the database. New facts in turn, can render possible execution of subsequent rules.

11.3 Expert systems

Expert systems are one of artificial intelligence methods [95]. They had been developed in the middle of the sixties of the XX century [96]. They are computer programs, which store knowledge from a specified, well documented area and allow for its usage in order to solve problems without an expert's participation [95]. The idea behind building and functioning of expert systems is based on acquisition of knowledge from an expert, saving it in a knowledge base and permitting access to that knowledge to persons seeking solution to a particular problem. The knowledge acquisition requires cooperation between the—domain expert and the so-called knowledge engineer building and supplementing the knowledge base of an expert system. According to some authors, the process of knowledge acquisition constitutes the most significant bottleneck during implementation of expert systems [97] in comparison to other methods of artificial intelligence, such as e.g. artificial neural networks. Operation of an expert system reminds an expert consultation also in that respect, that if necessary the system asks about required, lacking information, and explains why certain information is vital when solving a certain problem. In order for building knowledge bases of an expert system to be justified, the problem pending solution, should satisfy the following conditions [95]:

- knowledge from a given area needs to be precisely determined,

- domain experts exist,
- problem to solve is neither trivial nor particularly complicated,
- alternative techniques are not applicable to solve the problem,
- benefits following from application of expert system are significant,
- problem domain expert shows willingness to cooperate.

Basic modules of an expert system are (fig. 48) [94]:

- data acquisition module,
- knowledge bases,
- inference engine,
- explanation module,
- user interface.

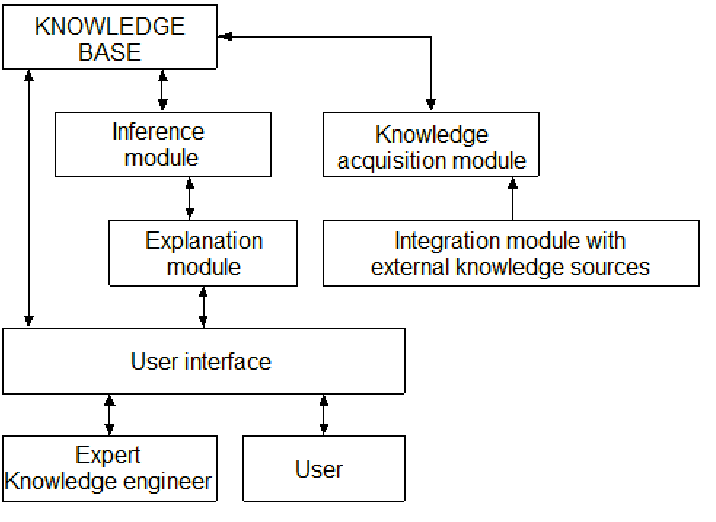

Fig. 48. Expert system architecture [94]

Knowledge acquisition module allows for building and supplementation of already created knowledge bases. Usually is operated by a knowledge engineer, who fills the base, on the basis of information obtained from a domain expert. A knowledge base contains knowledge regarding current parameters of an object and knowledge describing proceedings in certain situations (in rule-based systems it is a set of rules). In rule-based expert systems, the element responsible for verification of facts conformity with standards included in antecedent and with execution of conclusions from the consequent is the so-called inference engine. Based on comparison between facts and premises, the inference engine determines feasibility of rules. Following from execution of rules, the knowledge bases are supplemented with new facts.

There are two fundamental types of reasoning [94]:

- forward chaining,
- backward chaining.

Forward chaining is also called data-driven chaining [94]. The inference engine analyses, which premises of rules are possible to confirm. As a result of executing a rule in the knowledge base new facts appear, what can lead to confirmation of other rules. The process is repeated until the moment neither rule can be confirmed. This method's trait is expansion of fact base [94]. New facts can occur in the base not only as a result of rules' execution, but also they can be added by the user prior to reasoning process commencement. The process of forward chaining can be compared with issuing diagnosis (conclusion) based on symptoms (facts).

Backward chaining in turn runs into opposite direction. It starts with definition of hypothesis, which similarly to a fact adopts the form of trio <OAV>. The purpose of backward chaining is confirmation, or negation of a hypothesis. The inference engine verifies the feasibility of rules, which contain conclusion corresponding to hypothesis. Confirmation of premises of some rules might require verification of other rules, which in conclusion contain facts needed for confirmation of premises of the rule analysed. If there are facts lacking from the knowledge base and they cannot be obtained by calling other rules, the system can proceed to conversation with user. Backward chaining is also called goal-driven chaining [94]. The inference engine is responsible also for determination of rule execution order, in case when existing facts allow for execution of more than one rule at a time. Different strategies can be used here, e.g.: determination of rule priorities, deletion from the list of rules one has already used, or usage of the most frequently used rules. The explanation module is responsible for explaining to user, when the system has drawn certain conclusions – performed conclusion.

11.3.1 Tools for building expert systems

Expert systems can be created from scratch, just like other computer programs using various programming languages, universal ones such as *C, Pascal* etc to start with, and more appropriate symbolic languages like *Lisp* or *Prolog* or languages for building expert systems like *CLIPS*. They can also be created using dedicated tools such as shell expert systems or meta-expert systems. Shell systems are programs with implemented inference engine and explanation module, but with empty knowledge base. Meta systems are in turn expert systems intended for building expert systems [66]. Examples of shell systems are the *Jess* system and *PC – Shell*. The most popular programming languages used for implementation of issues related to artificial intelligence are:

- *CLIPS* (C *Language Integrated Production System*),
- *PROLOG (fr. PROgrammation en LOGique),*
- *LISP* (*LISt Processing*) – functional programming.

Prolog is a language of logic programming using the backward chaining mechanism. LISP in turn has not an in-built inference engine, but it can be easily implemented in it. A program written in the LISP language consists of lists being ordered element sequences. Those elements can be both functions, names, numbers and other lists. In turn the most simple in use and at the same time created with building of expert systems in mind, is the CLIPS. Due to built-in strategies of solving conflicts between rules, and implemented inference engine, it is going to be discussed in broader manner.

The *CLIPS* was initially a rule-based language using forward chaining. Later it had been developed i.a. with paradigms; procedural and object [98], [99]. The fundamental form of data representation in that language are facts, stored in the fact-list. Facts are used by rules in the process of reasoning. They adopt one of two forms: ordered and non-ordered. Ordered facts are composed of a symbol and any number of fields separated with spaces. Wherein a fact consisting of only a symbol is acceptable. Usually the first field is a symbol denoting relation, which refers to remaining fields. Fields can be of one of fundamental types, apart from the first one, which is a symbol.

In turn objects in the *CLIPS* language can be of one of two kinds: one of fundamental types or an instance of class defined by user.

An important element of the language is the so-called agenda, so the list of non-executed rules, whose conditions are satisfied. The order of rules on the agenda is decisive of their verification order. The rule on top is executed first. When the rule makes the agenda, the following factors are deciding about its position:

- the rule is located above rules of lower priority (*salience*) and below rules of higher priority,
- after determination of order amongst the rules of the same priority, the current strategy of solving conflicts is used (described below),
- in case when a rule is activated through insertion or deletion of a fact and its position on the agenda is impossible to determine on the basis of two above-mentioned criteria, the position is determine arbitrarily.

CLIPS has seven strategies of resolving conflicts (*depth, breadth, simplicity, complexity, lex, mea, random*) used for determining the order of executing rules of the same priority. Change in strategy causes alteration in order of executing rules on the agenda according to the new strategy. The default strategy is *depth*. In the *depth* strategy, newly activated (added to agenda) rules are located below rules of the same priority. In the simplicity the rule is situated above rules of the same of greater specificity (within the bounds of rules of the same priority). Specificity of a rule is determined based on number of comparisons, which have to be made within the left side of the rule (the conditional part of a rule). Every comparison to the constant increases the value of specificity by one, similarly as every function calling does. Boolean functions do not increase the value of specificity, contrary to their arguments. In the *complexity* strategy, a newly activated rule is situated above rules of lower or equal specificity (within the bounds of rules of the same priority). In the *random* strategy, every rule activation has got a random number assigned, which is later used for determining the position of the rule within the rule of the same priority. That number does not change even after change in strategy, therefore the same order of rules will be restored, once the *random* strategy is chosen again.

LEX strategy corresponds to strategy of the same name in *OPS5* language. In the first place the *recency* of the pattern is checked, which activated the rule in order to determine the location of the rule. Every fact has got a *timetag* assigned, which stores relative addition time. Relative *timetag* value indicates, that the given element was added later.

Determination of new position for a new rule on agenda, amongst rules of the same priority, requires sorting every rule's *pattern entities* according to the *timetag* value in descending order. Activated rule with newer patterns is situated before rules, whose patterns are older. If that comparison is inconclusive, that is when *timetag* values are identical, then the priority is held by the rule of higher quantity of those tags. If both rules are the same in that respect either, then the rule positioned higher is the one of higher specificity value.

The last strategy is *MEA*, an analogous strategy exists in the *OPS5* language. The activated rule, whose first *timetag* is greater, is situated before the rule of smaller first *timetag*. If that comparison is inconclusive, the *LEX* strategy is used next.

11.3.2 Shell expert systems

Shell expert system is a computer program, which is intended to simplify and shorten the time of building an expert system. It is a finished expert system without a knowledge base [66], [100]. Shell expert system allows for concentrating on building of the knowledge base, because it has inference engine and explanation module implemented, and usually graphical editor of knowledge base. An example of shell expert system is the software included in the SPHINX artificial intelligence suite from the AITECH company [101].

Building an expert system takes place with use of the following two programs:

- *CAKE* – a program which has amongst others knowledge base editor (attributes, facts, rules) and editor of the control block (fig. 49),
- *PC – Schell* – shell expert system. It allows for using knowledge bases built by means of the CAKE tool.

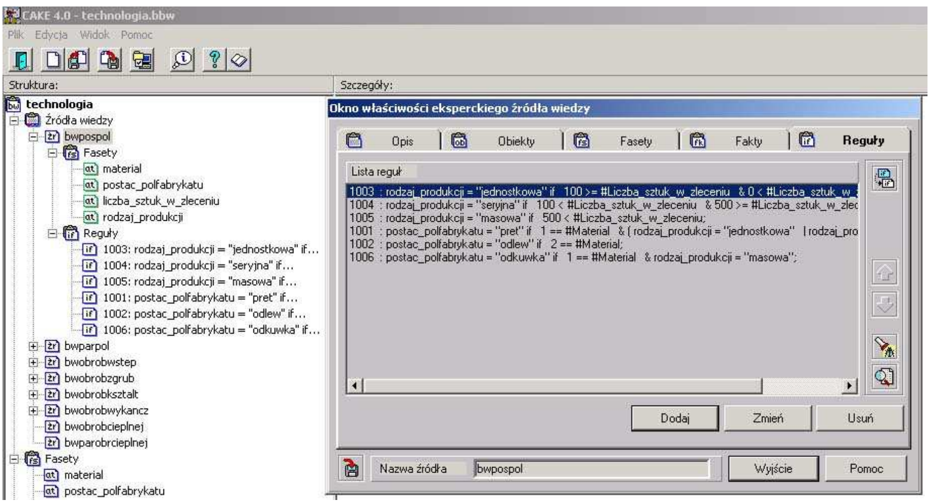

Fig. 49. *CAKE – editing rules* [102]

The SPHINX suite uses rule-based knowledge representation [103]. It allows for creating facts composed of trios <OAV> as well as duos <AV>. Attributes can be defined as symbolic, storing alphanumeric sets as well as numeric – storing numbers. Acceptable values of attributes can be restricted by intervals or lists of permitted values. Moreover there is a possibility of defining the attribute's type as a so-called some-of, which permits existence in the knowledge base in of more than one fact composed of the same elements <OA>, but differing in value.

All allowed types of attributes are presented in fig. 50.

Fig. 50. Available types of attributes in the Sphinx system from AITECH Sphinx

SPHINX supports both backward and forward inference engine. Knowledge can be additionally divided into so-called tables. SPHINX possess an in-built language allowing for i.a. writing control programs, responsible for usage of the knowledge base and controlling the course of dialog with the user. One can use the built into *PC-Shell* expert systems also from the level of different programs by using either *OLE* or *DDE* mechanism.

11.3.3 Knowledge processing in rule-based expert systems

Based on rule-based models are many available shell systems and other tools aiding building expert systems. Below were described main problems and constraints related to application of that model of knowledge representation in aiding works connected to technology planning.

In rule-based expert systems the effect of confirmation of a rule's premise – during forward chaining – is addition to the knowledge base of a new fact – such practice takes place amongst others, in *PC-Shell* shell expert system. In the *CLIPS* language there is a possibility of adding several facts within conclusion of a single rule. In the PC-Shell system such fact can be obtained through creation of extra rules with the same block of conditions, but other conclusions. Effectively, during backward chaining the number and type of added facts is not always easy to predict, because it is not only dependent on initial facts, but also on the number and content of the rules. In case of backward chaining which concludes with a hypothesis confirmation, in the knowledge base a fact defined in hypothesis is not going to occur. On the other hand, facts can be added which result from e.g. the dialog with user, necessary for hypothesis confirmation. In case of hypothesis being not confirmed, the user is not informed about reasons of that situation coming about, because there are several possible:

- Lack of one or more facts required by the rules' premises – the situation takes place, if there is a rule, whose conclusion resembles the hypothesis, but the inference mechanism is not able to confirm it, due to the lack of at least one fact determined in premises.
- In the knowledge base there are facts rendering impossible to execute rules – attributes describing an object, appearing in the premise of the rule capable of confirming the hypothesis, they exist and have particular values, but their values do not resemble the premises. E.g. one of rule's premise requires a fact in form of the following trio:

  (part model, mass, 3.5),

  but there is a fact in the knowledge base:

  (part model, mass, 3.8),

  and there are not any other facts composed of the duo <part model, mass>.

- The hypothesis describes the case, which cannot take place. Such situation may occur, when hypothesis contains the fact, which does not appear in conclusion of neither of rules and it is not possible to obtain it by way of conversation. The second case is often theoretical, because in practice operation of an expert system aims at determining a parameter demanding usually complex reasoning, if that value was possible to obtain by way of conversation, with searching through rules, it itself should not be the reason for building an expert system.
- Wrong hypothesis – a hypothesis has usually the form of an alphanumeric set containing the quality symbol, determining in such ways the expected value of the attribute. In case of an error in that set, being for example alteration of character in the name of the attribute, the inference mechanism will inform about the lack of possibility to confirming the hypothesis.

Lack of feedback information in the event of hypothesis being disconfirmed, sometimes forces the time-consuming knowledge base searching. The user of the finished system can interpret it as negation of the hypothesis, and that is only one of possible causes of such situation.

Coupled with rule-based expert systems is knowledge representation in form of trios <object, attribute, value>. The knowledge base contains a set of facts consisting of <OAV> trios. In the *SPHINX/PC-Schell* shell system a fact can be also constituted by the <AV> duo. The attribute of the <OAV> notation resembles a variable, because it has a type, it differs from it with the possibility of restricting acceptable values, what is missing from the variables of simple type. In turn the object is the first element of the trio <OAV> is the subject of analysis/diagnosis, and not an occurrence (instance) of a particular class as it is in the case of object programming. An object cannot inherit properties from other objects, neither can it be linked with other objects with the parent-descendent relation. It renders impossible to create a hierarchical structure, which is required at many stages of a generative CAPP system's functioning, amongst others for presentation of a part's model structure in boundary representation. A model consists of separate geometric objects, which consist of faces, which in turn are described by surfaces and loops etc. until the required level of detail. Similarly a technological process consists of operations, occurring within their procedure's bounds etc. Hence the application of rule-based expert systems is limited to aid the process of making rudimentary decisions. An example of such decision is selection of a tool base on traits of a single feature.

The next problem, connected to rule-based model of knowledge representation, is lack of possibility to enter openly into the base several objects of the same type. This constraint causes problems at the majority of decision stages connected to technological process planning. For instance, at the stage of processing CAD data there is any number of faces and other geometry elements of a model of the same type. Groups of faces should be transformed into technological objects, based on their traits as well as geometric relations between them. However in representation based of <OAV> trios the rule is strictly related to a particular object (object name) or objects. Moreover, at some stages of a CAPP system operation the order of facts is vital, especially at the stage of identification and sequencing of machining operations. In rule-based systems there is no mechanism for managing the order of facts, therefore the issue of realising sequencing does not come easily in those system.

The next drawback of expert systems is long time of and problems related to acquisition of knowledge. Several contributing factors, amongst others problems with translating the intuitive knowledge into rules, and the reluctance itself on the expert's part to reveals secrets of their profession to third party. Building of a completely functional expert system requires certain programming skills, in order to build a base or at least a so-called control program. Hence presence of knowledge engineer is necessary.

Specification of crucial for technological planning constraints of rule-based representation and proposed mechanisms solving those problems are presented in table 5.

Table 5. Specification of important constraints of rule-based knowledge representation and developed solutions

Trait	Stage of CAPP system operation	Proposed solution
No mechanism explaining reasons for reasoning failure	Determination of individual process parameters – usage of backward chaining mechanism	Mechanism for tracking and controlling the course of reasoning process informing user about the reason of possible failure
No relations between objects	Stages from TF recognition to stage of generating the technological process structure, inclusive	Hierarchical knowledge base structure, allowing for modelling parent-descendent relations between objects and using the same object names in different branches of its structure
No mechanism of object order management	Sequencing TF in order to determine to machining order	Mechanism of maintaining order of objects, rules allowing for modifying order of objects within the confines of a particular

		superior object
Necessity of building control programs, especially for handling complex cases	Application in CAPP system of rule-based shell expert system requires big programming outlays, in order to overcome constraints resulting from that method of knowledge representation	Dedicated rule classes for modelling decision processes at basic stages of generative CAPP system

Amongst the most important constraints one has to count the building of facts knowledge base, characterising with lack of dependencies between objects, rendering impossible to model hierarchical dependencies. Moreover, building of expert systems, even with the use of shell tools, is still a task requiring an appropriate knowledge from the scope of knowledge representation methods as well as programming skills.

12 Summary

The issue of designing workplace arrangement plan is particularly important, when a manufacturing system is subjected to reorganisation (reconstruction), new workplaces are added or it is designed from scratch as a new one. The way of allocating workplaces is influenced by substantial number of factors. They were described in detail in chapters of hereof paper. Application of computer techniques will allow for addressing the issue in a broader respect and quicker obtainment of solution.

Creation of LAYOUT plans is a long-term task, very expensive and every modification or change in hitherto state entails significant expenditure and cannot be achieved without substantial outlays. Application of information tools is capable of partly reducing the costs. Modelling and testing solutions prior to their implementation into simulation programs causes means of production to be used in a more effective manner. Realisation of a complete spatial model, and its needs oriented adaptation ensures an optimum utilisation of production space and abolishment of long and intersecting transportation routes. Workplace allocation planning is related to manufacturing technology intended for manufacturing given machine parts or assemblies. Correctly developed technology takes into account not only the specification of technological operations but also contains specification of workplaces where those operations can be executed. Workplace allocation should take into account the course of process, thus those issues are strictly interconnected and changes in each of those areas should be entered in parallel. CAPP computer systems aiding technological process planning should take into account the possibility of assigning alternative workplaces due to connection with LAYOUT planning for realisation of manufacturing processes.

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