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Survey paper

# A review of automated feature recognition with rule-based pattern recognition

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**Abstract**

Automated feature recognition (AFR) has provided the greatest contribution to fully automated CAPP system development. The objective of this paper is to *review* various approaches for solving three major AFR problems: (i) extraction of geometric primitives from a CAD model; (ii) defining a suitable part representation for form feature identification; and (iii) feature pattern matching/recognition. A novel, detailed classification of developed AFR systems has been introduced. This paper also provides a thorough investigation of methods for geometric feature extraction, emphasizing STEP standard application and, finally, a review of recent research reports in the field of AFR with rule-based feature pattern recognition. We discuss potentials and limitations of these approaches and emphasize directions for further research work.


*Keywords:* CAPP; Automated feature recognition; B-rep; STEP; Logic rules

**Contents**



## 1. Introduction

Generative CAPP systems, in general, should provide two groups of functions: (i) efficient translation of part's geometrical information, defined by a CAD system (low-level entities – vertices, edges, etc.) in part's manufacturing information, necessary for process planning and CAM (high-level entities – holes, slots, pockets, etc.) and (ii) definition of feasible process plan (selection of manufacturing processes, selection of a work piece size, selection of auxiliary tools, set-up planning, selection, determination and grouping of elementary machining operations, selection of machining systems, operation sequencing and optimization of operation sequences, selection of cutting tools, determination of cutting parameters and conditions, tool path

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determination, selection of quality inspection methods, cost analysis, optimization of process plan elements and CNC code generation and verification).

Speaking of first group of functions, there are three strategies, all based on form feature concept, but differing in methods of form feature determination:

(1) design-by-feature – DBF;
(2) automated feature recognition – AFR; and
(3) interactive form feature definition.

Design-by-feature demands the existence of a form feature library, accommodated not to part function, but to part manufacturing needs. Product model is formed by using only form features from the library. Automated feature recognition comprises browsing some type of part representation aiming to find information, which characterizes singular form feature types. All approaches in this field have a unique goal: to form an algorithm capable of recognizing any possible type of form feature, without any interfering of manufacturing engineer. Interactive form feature definition is a system in which user selects a form feature set, determines recognition parameters to those features and then the system, using those instructions, performs an automated recognizing, whether directly in CAD model of the part, or in some structure developed from it.

In this paper, several AFR systems are discussed. All of them have to provide the solution for these interrelated tasks: (i) extraction of geometrical features from CAD model of the part, that are necessary for part representation suitable for form feature recognition. Boundary representation (B-rep) has most commonly been used; there is relatively rare usage of constructive solid geometry (CSG) part representation and, also, a few research approaches, based on wire frame part representation, have been reported. In B-rep based systems, these features comprise vertices, edges and faces of the part, in wire frame based systems vertices and edges and in CSG based systems geometrical primitives, such as sphere, cylinder and so on; (ii) formation of part representation suitable for form feature identification – in systems based on B-rep and wire frame representation topological linking of geometrical features is made, whereas in systems based on CSG the linking of geometrical primitives is made through Bull algebra operations. A certain number of developed AFR systems are using direct browsing of CAD model of the part for form feature extraction; (iii) matching of form features, recognized in part representation attained as a solution to previous task, with patterns in form feature library and, in case of advanced systems, based, for example, on artificial neural networks, knowledge acquisition—new patterns can be made of unrecognized form features.

In corresponding literature, following terminology has most commonly been used: feature extraction as the term for the first and the second task resolution, and feature recognition—as the term for the second and the third task resolution, and often for resolution of all three tasks. The authors have an opinion that the most suitable term for description of the first task resolution process would be geometric feature extraction, for the second task—form feature identification, and for the third task pattern recognition, that is proposed in [1], too. The authors use term pattern to describe notion of predefined manufacturing form in knowledge library, which form feature identified in part representation is matched with.

Studies analyzing developed AFR methodologies can be found in numerous literature sources, such as [2–7]. In this paper, a novel detailed classification has been offered, which takes in account variety of approaches, particularly for each of three mentioned tasks. Table 1 illustrates this classification.

In the following text, a review of newer research results in the field of AFR with logic rule-based pattern recognition has been given. Methods based on B-rep part representation are specially emphasized, because CSG based approaches have not given effective results, from reasons thoroughly depicted by Subrahmanyam and Wozny [4].

## 2. Methods for extraction of geometric features

Methods for extraction of geometric features from CAD model of a part can be divided in external and internal ones [8].

Table 1
Classification of AFR approaches

| Form feature extraction | | Pattern recognition |
|---|---|---|
| Geometric feature extraction | Form feature identification | |
| 1. External approach<br>2. Internal approach | 1. Syntactic pattern recognition<br>2. State transition diagrams and automata<br>3. Logic (if–then) rules and expert systems<br>4. Graph-based approach<br>5. Convex-hull volumetric decomposition<br>6. Cell-based volumetric decomposition<br>7. Hint-based approach<br>8. Hybrid approach | Logic rules |
| | 1. Graph-based approach<br>2. Face coding<br>3. Contour-syntactic approach<br>4. Volume decomposition | Artificial neural networks |

Internal approaches comprehend use of API (application protocol interface) of the software by which the part was designed, in order to access topological and geometrical information relating to the part. In external approaches CAD model of the part is exported from software by which it was designed in a neutral data format (STEP, IGES, ACIS, etc.) ASCII file. That file is then translated (using interface program—written in Prolog, C++, or some other program language) in a part representation suitable for form feature extraction [9]. Though there are many research results based on usage of other neutral data formats that have been mentioned here, a special attention in this paper is paid to STEP, which has included advantages of all previous formats.

STEP format has been specified through a series of standards ISO 10303. These standards aim to provide detailed information about product, along with neutral mechanisms for exchanging product data among all the systems that take part in product life cycle, including design, manufacturing, reliance, maintenance and removal. STEP is capable of describing part's geometry, topology, tolerance, relations with other parts, various attributes and contingence to appropriate assembly. For these purposes, STEP is using formal specification language EXPRESS ([10], ISO, 10303-11), which enables precision and consistency of part representation and facilitates the development of implementation models. When it comes to data exchange, EXPRESS specifications are translated to a neutral ASCII file, using methodology defined by standard ISO, 10303 (part 21) [10].

For each application field STEP defines particular application protocol, which describes the scope, the information to be exchanged or archived, methodology of testing and a user guide for implementing the application. The aim is to make an integrated product information database, which all the subjects taking part in product life cycle can access. Application protocol for process planning using machining features is defined by ISO, 10303-224 standard (AP224) [10]. It contains all the information needed to manufacture the required part, including the materials, part geometry, dimensions and tolerances. The product definition in AP224 contains the shape representation as well as a definition of the machining features. The definition also contains the initial shape of the material before machining, which is very important for production of valid process plans.

STEP standard application is emerging in all industrial domains. Speaking of CAx applications, all important CAD software packages (e.g. Pro/ENGINEER, CATIA, Unigraphics, I-DEAS, etc.) have developed and commercialized CAD-STEP interfaces [11]. An example of generic STEP based CAPP system is GPPE (generative process planning environment), developed at SCRA (South Caroline Research Authority). It implements a technique called rapid acquisition of manufactured part (RAMP), based on application of manufacturing features defined by AP224.

There are numerous examples of application of STEP in developed CAPP systems. One of them is system for form feature extraction, which is presented in Bhandarkar and Nagi [11] (Fig. 1). The input in the system is STEP ASCII file, exported from the model of the part, designed using any software, which enables STEP interface. Then it is browsed by a program written in C++, which matches the structure of ASCII file with patterns in a database, developed using appropriate standard for particular type of part representation. If a structure in ASCII file, alike to a pattern in database, is found, it will be translated to appropriate entities defined by AP224.

Another interesting example of AP224 use for AFR is described in [12]. The system consists of an expert system with external knowledge base, which can easily be updated and adjusted to various technological applications. Knowledge acquisition is made by using ST-Developer graphic tool by StepTools Inc., which is used to visualize information given in STEP ASCII file. System outputs are NC code and process plans in *.rtf and *.xml format. Some examples of developed algorithms for geometric dimensions and tolerances extraction have been given in [13], for particular form features and, also, for the cases of their intersection. STEP neutral format can also be implemented in Feature Based Design Systems, but then we have form feature translation, not extraction [14].

## 3. Methods for automated feature recognition with rule-based pattern recognition

The methods for automated feature recognition with rule-based pattern recognition apply a common basic principle: the structures identified in a part representation, formed using one of the methods given in Table 1, are matched with some pattern in the knowledge base, using if–then rules. It is essential that these rules provide uniqueness of form feature definition: there must not exist two forms with a unique definition or one form with more than one definition in the knowledge base. If set up

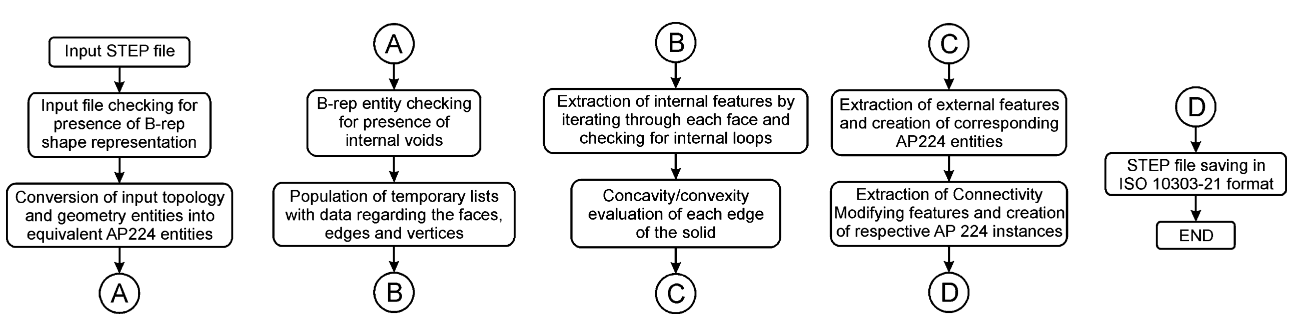


Fig. 1. Diagram of form feature extraction process based on AP224.

correctly, these systems provide accurate and thorough form feature identification. The major disadvantage of these systems is the lack of knowledge acquisition mechanisms, which becomes a serious problem when form feature is extracted that cannot be matched with any pattern in the knowledge base.

There are numerous systems, developed using logic approach for manufacturing pattern recognition, that differ one from another in a model of part representation in which a form feature identification is to be carried out: (1) syntactic pattern recognition; (2) state transition diagrams and automata; (3) logic (if–then) rules and expert systems; (4) graph-based approach; (5) convex hull volumetric decomposition; (6) cell-based volumetric decomposition; (7) hint-based approach; and (8) hybrid approach.

### 3.1. Syntactic pattern recognition

In syntactic pattern recognition method, a model of the part is made using semantic primitives written in some description language. A set of grammar, which consists of some rules, defines a particular pattern. The parser for input sentence analysis has been then used to apply a grammar to the part description (entities connected to form a part). If the syntax agrees with the grammar, then the description can be classified in a corresponding class of forms (pattern). There are three components of pattern recognition, Fig. 2 [2]. Input string represents semantically unknown grammar. Form semantics will be recognized if it can be classified in a group of predefined forms (pattern). Classification is made through form syntax lookup. Pattern syntax is also defined using grammar.

Syntactic pattern recognition demands form primitives to be defined, and, also, automated translation of design model in a part description suitable for syntax analysis (string) to be provided. This is the earliest concept of AFR, introduced by Kyprianou [6]. This method has been more often and more successfully implemented for 2D form feature recognition. If used for 3D feature recognition it had to be previously translated in 2D part model.

One of these systems has been presented in [15]. The system is especially interesting because it takes a wire frame part representation model, imported from AutoCAD *.dxf file. It is developed for prismatic parts, a case of syntactic pattern recognition implementation not so often met in practice. The wire frame model (3D) is translated in a vertices-edges graph (2D), for each one of six boundary planes of a parallelepiped. This system provides the recognition of several form features: hole, step, slot and protrusions with orthogonal boundary faces. Hole is a basic feature, and all other are derived from it: steps are holes without two faces, slots are holes without one face, and protrusions are treated like a combination of slot and step manufacturing. In extension, graphs are translated in strings of shape primitives, using methodology illustrated by Fig. 3, and then strings are matched with the patterns in a knowledge base.

A more recent technique that may be included in syntactic pattern recognition group of approaches is so-called edge boundary classification (EBC), presented by Ismail, Bakar and Juri in a series of papers (2002–2005). It considers the use of spatial addressability information of solid models that identifies the solid and void sides of a boundary entity. For each edge loop identified in B-rep model of the part, an EBC pattern can be formed from the result of classifying a set of test points (located at a close proximity to the edges that form the loop) with reference to the solid model. Depending on whether these test points qualify to solid or outer space, they are coded, and the string of these codes for each edge in the loop forms the pattern that can be used for form feature recognition. This approach can be applied for recognition of some features in parts to be produced on 2D NC machines: pockets, slots and steps consisting of planar and/or semi-cylindrical faces [16] and, also, for cylindrical and truncated conical features, both in prismatic and rotational parts [17]. The advantage of this technique is in the fact that it has the ability not to be affected by geometric and topological changes, except by those affecting primary faces. This implies that no post-processing is required, not even in case of interacting features. Its shortcoming is in complicated pre-processing for form feature identification: extraction of all relevant geometric and topological data, presentation in a format suitable for use by the EBC algorithms, establishing spatial addressability information and EBC patterns creation.

The main shortcoming of the syntactic pattern recognition is its area of application, limited to 2D prismatic parts, rotational parts with turning features and axis symmetric volumes. The implementation of this technique in the systems for non-axis symmetric 3D part or rotational parts with non-turning features has not been very successful, mostly due to restrictiveness of pure syntactic representation.

### 3.2. State transition diagrams and automata

The first application of state transition diagrams and automata for AFR occurred in CIMS/PRO CAPP system,

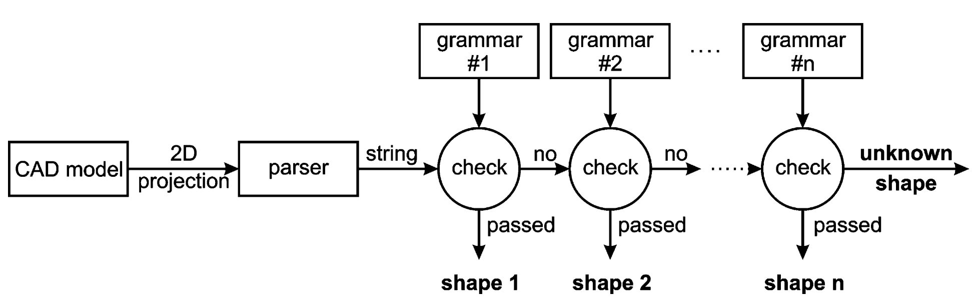


Fig. 2. Syntactic pattern recognition architecture.

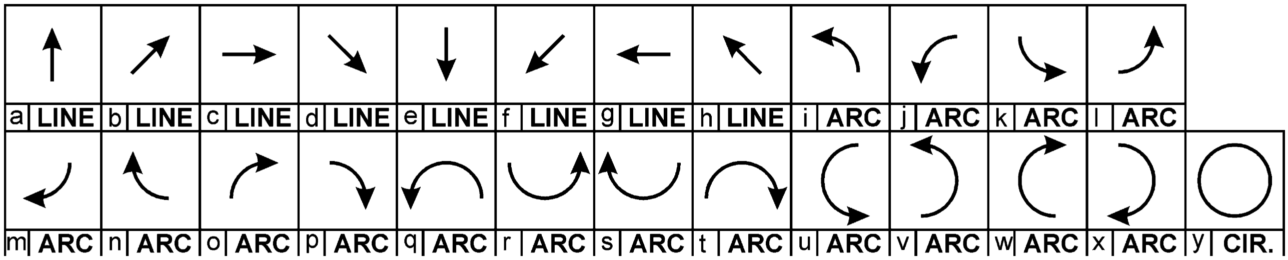


Fig. 3. Shape primitives.

which was developed in 1979 under supervision of prof. K. Iwata [2,3]. State transition diagrams and automata are similar to context free grammar. If the states are replaced with non-terminate, and the inputs with terminate symbols, then a grammar can be written. Part model is formed by using the ''space sweeping'' operators as the union of volumes obtained in that process. For rotational parts, sweeping represents part contour rotation around its axis, whereas, for prismatic parts, sweeping is translation of a face in some direction. CIMS/PRO part representation for AFR for prismatic parts is illustrated in Fig. 4a. An example of this approach implementation in rotational parts families classification (a complex part, grammar for the complex part and an automat for group technology grammar), is illustrated in Fig. 4b [18].

### 3.3. Logic rules and expert systems

Henderson and Anderson [19] introduced the logic approach. A set of production rules, IF C1, C2, C3 ... Cn THEN A, defining form features, provide the patterns for AFR. If the conditions (C1, C2, C3) predefined by some pattern are satisfied, then the structure in the part representation that agrees with them is recognized as a corresponding form feature A. All the systems described in the third chapter of this paper implement a logic approach as a model for pattern recognition. The systems described in this Section 3.3 are specific to have logic approach implemented in the level of geometric information extraction. In these systems, no particular part representation needs to be defined for geometric feature extraction, as it is the case in all other approaches.

One of such systems is presented in [9,20]. A model of the part is translated from 3D solid modeler in IGES inscription (Fig. 5a). Then, using a utility program, IGES data are converted in Prolog facts. The first stage of the recognition process is face extraction and base faces (base face is a feature face which has a concave adjacency with at least one feature face) determination. Then, the boundary faces are being determined (Fig. 5b). The main criterion for a form feature matching (except for the holes) is the number and type of boundary faces. For faces satisfying the same basic conditions, additional conditions are introduced. The features that system may recognize are pocket, slot, blind slot, step, corner step, hole, blind hole, countersink hole. A very similar system, also applying logic rules to a set of data obtained from neutral IGES file, aimed for CAPP of prismatic parts was developed by Bouzakis and Andreadis [21].

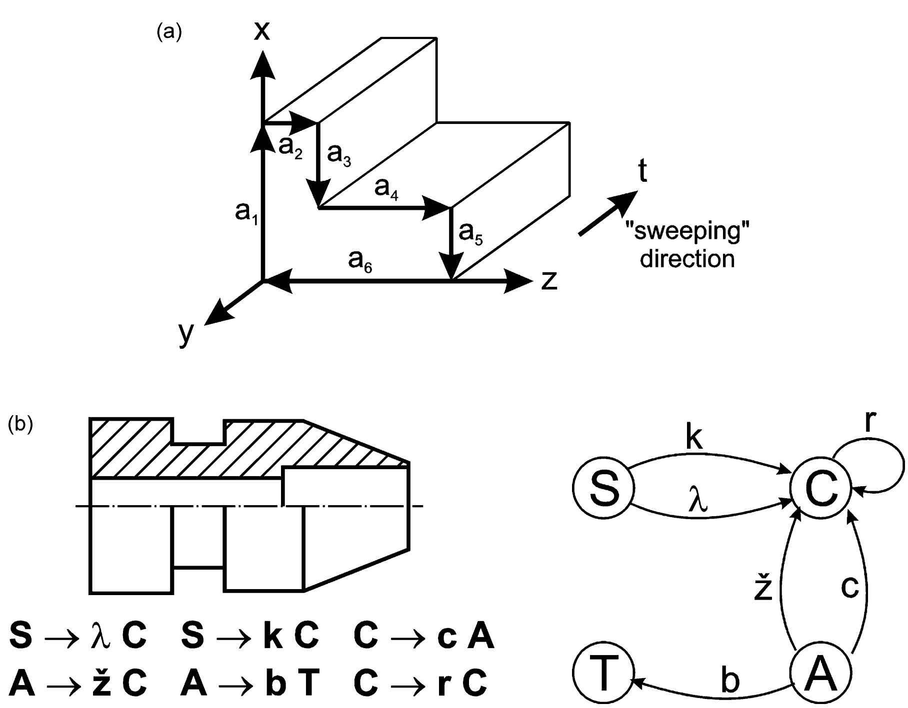


Fig. 4. (a) CIMS/PRO prismatic part representation; (b) implementation of automata in group technology for rotational parts.

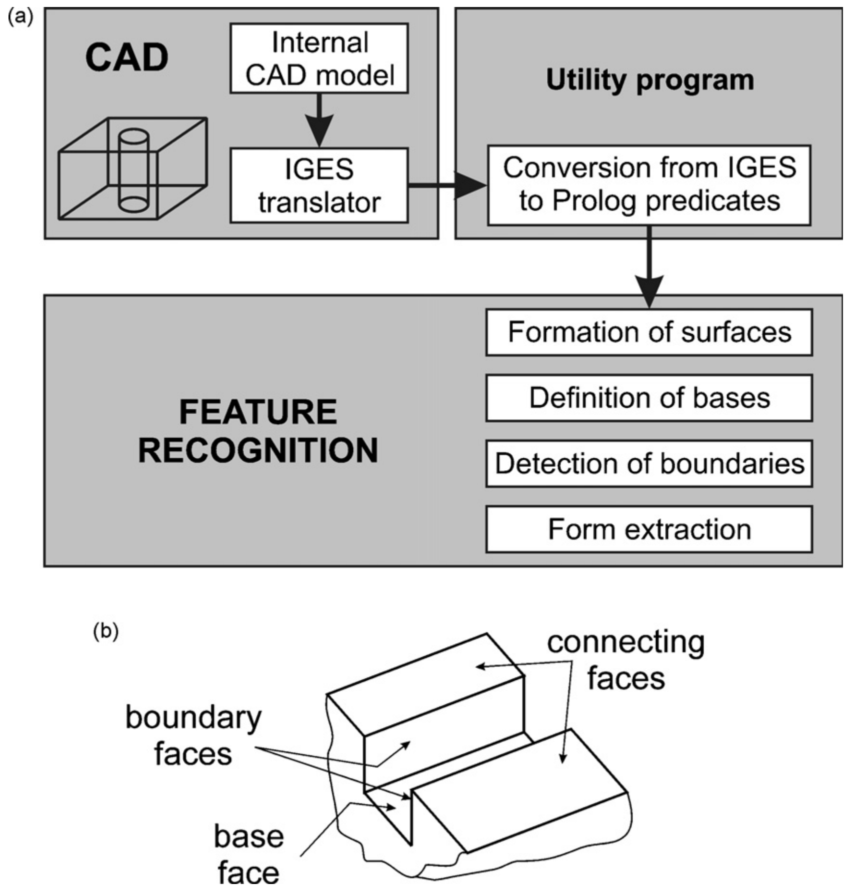


Fig. 5. (a) A CAD/CAPP interface model; (b) definition of the faces a form consist of.

Next example of logic approach implementation is given in [22]. A CSG part representation (less common in research practice) is used for geometric feature extraction, which is performed by browsing the *.txt file in SolidWorks application protocol interface, using a program written in Visual Basic. Recognition is performed by matching extracted forms with the patterns in Oracle database. The system is designed for the recognition of numerous types of forms that occur in prismatic parts, but it is not capable to recognize intersecting form features. Recognized forms are then used for automated process plan generation.

Rule-based method, as a kind of generalization of syntactic method, has proved to be more robust and handling more kinds of parts than syntactic method. Ambiguous representation and predefined rules needed for every conceivable feature, make rule-based systems overburden and inflexible.

### 3.4. Graph-based approach

The graph-based approach is developed by Joshi in 1987 [2], aiming to form such part representation in which a topological information and some geometric information of the part will be included. He envisaged attributed adjacency graph—AAG in which B-rep model of the part (designed in some solid modeler) is transformed. AAG is a graph in which every arc takes attribute ‘‘0’’, if its nodes have a concave adjacency relation, or ‘‘1’’, if they have convex adjacency relation, Fig. 6a and b. Form features represent subgraphs of part AAG and form feature recognition becomes a process of finding such subgraphs that can be matched with the patterns from the database. Subgraphs are analyzed by using logic rules, called recognizer. Such an approach is called subgraph isomorphism and represents a long-term and computationally demanding process of AAG structure browsing. The alternative method is graph partitioning/graph isomorphism [7]. Extraction is performed by parsing the AAG in nodes which have all adjacent faces convex (all arcs converging have attribute ‘‘1’’), Fig. 6c. AAG concept, in its original form, suffered from two major shortcomings: possibility of application only for negative, polyhedral objects (polyhedral shaped intrusions, without curved faces) and impossibility of extraction of boundary faces, but only basic faces. The problem of extraction of the faces which are connected with one more face only (like top surface of cylindrical protrusion), or with two more surfaces (cylindrical protrusion envelope) has been discussed by Gavankar and Henderson [23] and solved by using special algorithms.

The shortcomings of the AAG can be significantly diminished through the concept of multi-attributed adjacency graph—MAAG, assigning the attributes which more precisely descript adjacency relations (e.g. if plane and curved face make a convex angle (270°) then the attribute is ‘‘2’’). If MAAG is represented with a matrix, then such system is called multi-attributed adjacency matrix—MAAM. The recognition process

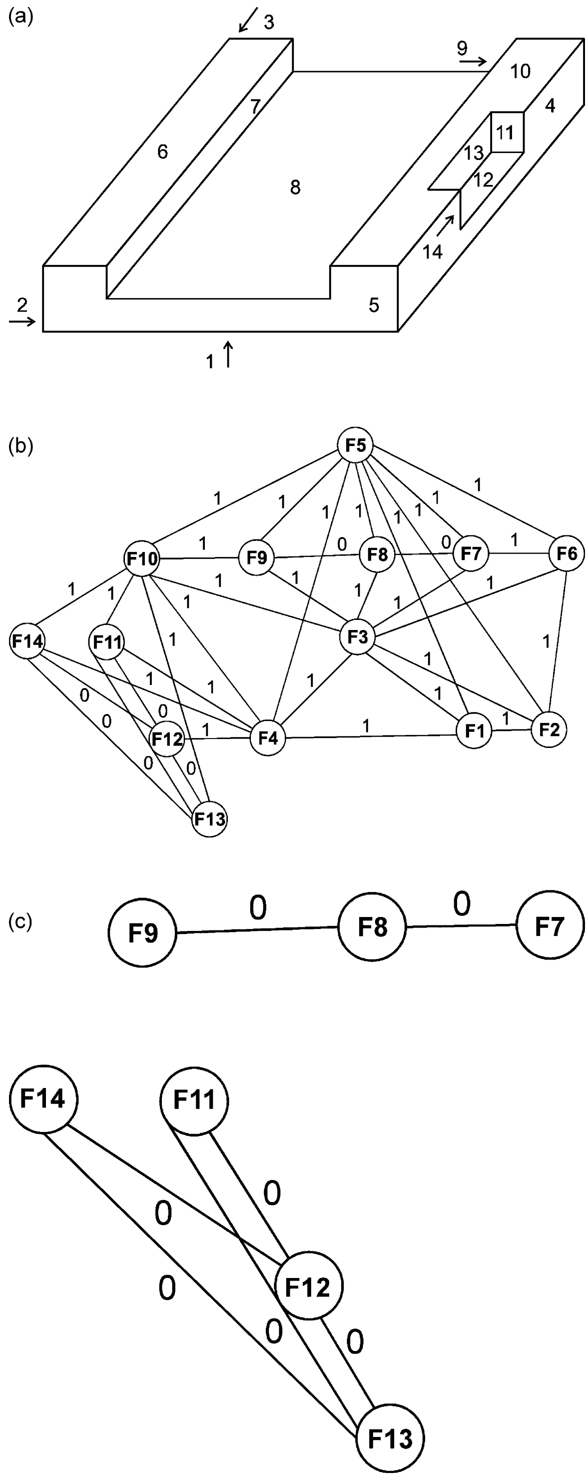


Fig. 6. (a) Part; (b) AAG of the part [69]; (c) AAG subgraphs.

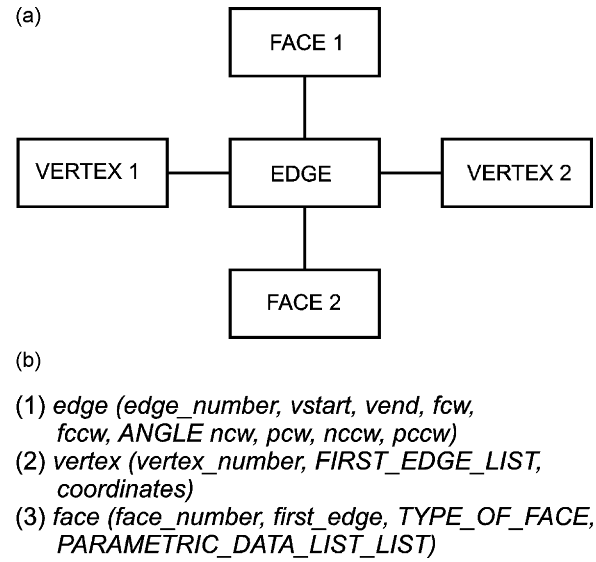


Fig. 7. (a) WEDS; (b) EWEDS (Prolog facts) with additional information (upper case letters) [24].

is performed over adjacency matrix schemes, which are predefined for each elementary form.

One of numerous systems designed upon MAAG implementation was introduced by Venuvinod and Wong [24]. This AFR system is particular in following: B-rep of the part, whose elements were extracted from CAD model, is formed using so-called EWEDS data structure. EWEDS (enhanced winged-edge data structure) presents an enhanced version of the ''winged-edge data structure'', emerged by Baumgart in 1974 [24], Fig. 7a. WEDS is an edge-based data structure, which provides information of the object's faces, edges and vertices in an explicit way. A pointer connects each marked face to each of its boundary faces. Likewise, there is a pointer to each of its bounding vertices (start and end). Every edge occurs in two faces exactly, once in the clockwise and once in the counter-clockwise orientation from object's outside aspect. In EWEDS a new level of data is added, relating additional information about edges, faces and vertices. In these data, that facilitate recognition process, the most important information relate to the type of each face, and convexity/concavity of the angle it makes with the adjacent faces.

In newer researches, Venuvinod, Wong and Yuen experiment with MAAM concept [25] and seek for ''less expert-system and more algorithmic'' way for form pattern recognition. They invented a detailed coding system for description of so-called ''primitive template features'' identified in EWEDS B-rep. These features, which by definition cannot be further decomposed in a reasonable way, are used for identification of feature relationships. The process results with a multi-layered representation of a part containing feature relationships on the first level, primitive template features and their variations on the second, face-edge MAAG on the third, EWEDS B-rep structure on the second and CAD file on the fifth level. This structure gives an opportunity for higher levels (the first and the second) to be CAPP domain-specific, based on the same geometric reasoning in lower levels, thus avoiding unnecessary repetition of geometric analysis for each of the CAPP domains. In [26] the authors gave a betokening example of graph-based feature recognition implementation in their GCAPPSS system aimed for concurrent engineering.

The ''rock'' that sunk the most of graph-based AFR systems has been the problem of interacting features. Marefat and Kashyap [27] were the first to try and solve this problem by restoring the missing arcs between the nodes in part's graph

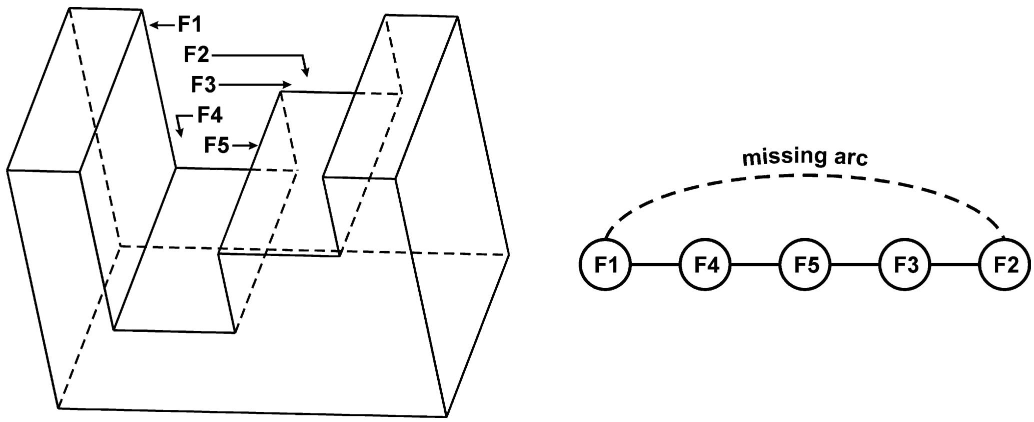


Fig. 8. Missing arc in intersecting features.

representation (which stand for the edges between the faces which disappear when two or more features interact, Fig. 8). However, this approach often led to wrong set of missing arcs, due to the ‘‘uncertainty’’ reasons [28]. While features interact, uncertainty develops as a result of non-uniqueness of the patterns associated with the topology and geometry of features in these interactions. Various techniques have been developed to investigate available abundance of geometric and topologic evidences, which if used correctly, can lead to the resolution of the uncertainty and therefore eventual recognition of the features. Two universal techniques for handling uncertainties and finding the exact set of missing arcs have often been applied in graph-based AFR systems: the Dempster–Shafer theory [27,28] and Bayesian probabilistic rules [29]. In the Dempster–Shafer theory, the missing links are identified from a set of possible missing links by accumulating both geometric and topological evidences using Dumpster's rule of combination. This method suffered from computational inefficiency, because of its incapability to recover more than one missing link at a time. Ji and Marefat [29] expanded the original algorithm [27] for missing arcs‘ restoration by using Bayesian nets. The pieces of evidence, which consisted of topological and geometric relationships at different abstraction levels, were combined to form a set of correct virtual links. These links were to be augmented to the cavity graph representing a depression of the object so that the resulting supergraph can be partitioned to obtain the features of the object. The hierarchical belief network was constructed on the basis of the hypotheses for the potential virtual links, which impacted the belief network through the amount of support for different hypotheses. This method was able to recover simultaneously all missing links and recognize more complex interacting features with improved recognition accuracy. However, it could not completely solve the problem.

Not all graph-based methods were based on face-edge graph. Qamhiyah et al. [30] proposed a feature extraction technique which was based on loop-adjacency hypergraph and was focused to obtaining generalized properties of the classes of features with planar faces only. This limited area of application is the major drawback of this technique.

The system presented by Huang and Yip-Hoi [31] is focused on so-called ‘‘high-level’’ features such as ‘‘stepped’’, ‘‘compound’’ and ‘‘array’’ features (Fig. 9). A feature relationship graph is used to organize primitive features in user-specific high-level feature patterns. In such way, at least these categories of interacting features may be recognized, but it requires extensive user intervention, reducing the level of automatization of this feature recognition system.

Di Stefano et al. [32] have proposed a system which is based on face adjacency multi-graph, precisely attributed to capture all properties that are important for the part's manufacturability. For example, the system can manage properties such as mutual relations between faces that are not necessarily adjacent: parallelism, coaxiallity and perpendicularity. The attributes of the nodes and of the arcs of the graph are arranged in order to obtain a unique representation, so-called ‘‘intermediate model’’ with a wide range of data needed for engineering oriented semantic recognition. The semantic construction is based on the concept of ‘‘semanteme’’: the minimal element of meaning that the system can manage and recognize in a geometric model

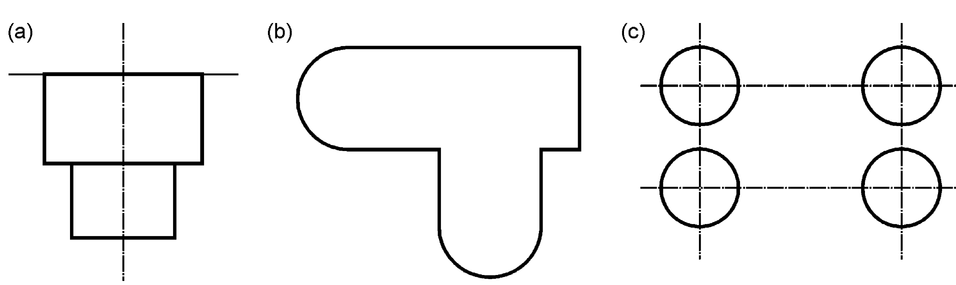


Fig. 9. High-level features [31]: (a) stepped features (profile combination); (b) compound features (path combination); (c) array features (instance combination).

which is related to some kind of machining context. This system may be capable of capturing a large quantity of procedural knowledge, directly from geometric model, but it depends of human intervention for its validation. Integrating the geometric modeling system with the feature-recognition system, as proposed by the authors themselves, may be an improvement of the proposed semantic recognition method, especially in the domain of interacting features, but it will drag this system even further from AFR to design-by-feature methods.

All graph-based methods require extensive pre-processing in order to construct representation for each part and each primitive and in most examples of their application only polyhedral parts are treated. Even when they are capable of successful recognition, there is no guarantee that the recognized feature will prove applicable in the sense of manufacturability, i.e. that they will be suitable for use in further other modules of a CAPP system. However, the main problem which graph-based methods could not effectively solve is the problem of interacting features. This drawback can be partially diminished by using various techniques of geometric reasoning. The other way is to enrich the feature library with as many interacting features as it is possible, treating them as singular features. This approach requires a lot of computational time for searching and pattern matching and does not give an universal and complete solution of the problem, because on and on a feature will occur which is not included in an existing feature library. From all these reasons graph-based approaches provoked larger investigation of alternative methods, such as volumetric and hint-based, to deal with interacting features.

Graph-based method reincarnated in emerging approaches which use artificial intelligence techniques for pattern matching (the third task of AFR systems), because of their flexibility and ability of knowledge acquisition which can be used for real-time extension of form feature library.

### *3.5. Convex hull volumetric decomposition approach*

Convex hull and cell-based decomposition are two approaches based on decomposing the input model into a set of intermediate volumes and manipulating the volumes in order to produce features; many researchers often give them a unique name: volumetric decomposition approaches ([5,6,33,7]; etc.).

In 1980, Kyprianou gave the original idea for convex hull approach [6], but it was Woo who initiated its implementation in 1982 [5]. A polyhedron convex hull is determined, circumscribed around a part. The difference in volume between the part and its convex hull is defined as an alternating sum of volumes (ASV). Kim [34] provided the method for convergence, initiating remedial partitioning procedure – ASV with partitioning (ASVP) and, since then, he and his associates (Wang, Waco, Menon, Parienté and others) worked hard to provide successful algorithm for this method implementation.

At first, this approach has more successfully been applied for polyhedral parts because of the complexity of the convex hull computation for curved objects. Other problems that emerged during the development of the method included: how to convert the set of alternating volumes into meaningful constituents of shape of the part and, further, into machining volumes.

Kim's approach, after several modifications proposed in order to give solution to the problems mentioned above, consists of multiple steps [68]:

1. Extraction of cylindrical hole features – an algorithm has been provided for extraction of holes (cylindrical surface closed at least at one position along its axis), illustrated in Fig. 10a, which is not part of the original work;
2. Polyhedral abstraction of blending and cylindrical faces – another algorithm has been provided for identification of blending and cylindrical surfaces (other than holes and with a constant radius only), Fig. 10b;
3. ASVP decomposition, Fig. 10c, adapted from [35]. The convex hull of a polyhedron is the smallest convex point set containing that polyhedron. The convex hull difference is the regularized set difference between convex hull and the polyhedron. The decomposition is recursively applied to the convex hull difference until it becomes convex, when the decomposition terminates;
4. Form feature decomposition, 10d. This step aims to give meaning to decomposed component combining them into high-level constituents of the shape of the part.
5. Conversion to machining features – a "positive-to-negative" conversion is applied to convert positive components of decomposed volume to negative features which represent removal volumes providing information about machining surfaces, tooling and sequencing. Geometric reasoning in

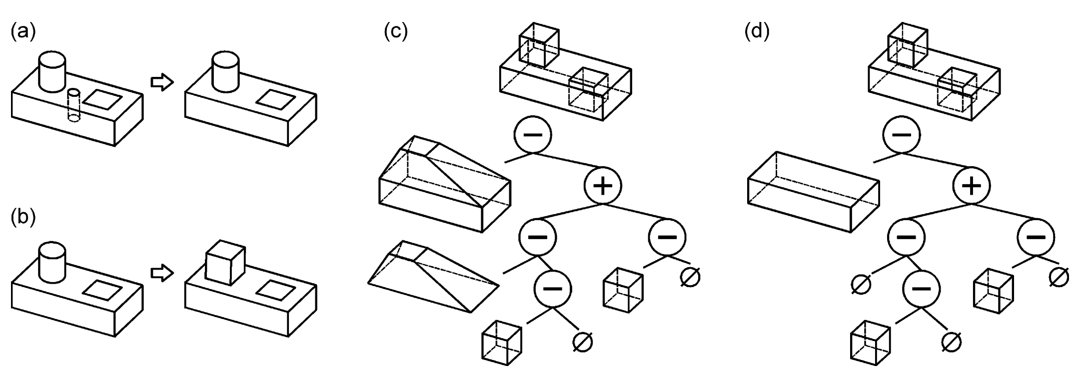


Fig. 10. Kim's approach: (a) extraction of cylindrical holes; (b) polyhedral abstraction; (c) ASVP decomposition; (d) form feature decomposition.

this step is different for specific manufacturing processes, as it is presented in [36]. In case of getting an unsatisfying result the alternative machining volumes can be obtained through the process of aggregation of negative features. Combining the positive components from previous step with the stock component a machining feature extraction for cast-then-machined parts can be obtained.

6. Re-attachment of cylindrical and blending information—blend is restored to a feature if it exists between faces which are all part of that feature; other blends between multiple features are stored as implicit relations between corresponding faces of those features.

Test of this system, performed on a group of various parts in several manufacturing domains (such as mill-turn process or machining of casting parts), produced promising results, presented in [68]. However, this system can deal only with polyhedral features and cylindrical features which interact with them in principal directions, with constant-radius blends. There are some other drawbacks which may produce unsatisfying and awkward results. The ASVP decomposition is completely separated from the feature recognition, and is not guided by the goal of recognizing specific types of features. Combining methods described in step 4 of the method are often incapable to produce recognizable features. Negative components (machining forms) obtained in step 5 should always be convex but the algorithm often terminates with a set of unmeaningfully shaped negative features. Proposed conditions for aggregating primitive components do not provide universal solution of the problem.

A lot of research teams experimented with this approach for feature identification in AFR systems.

An example of ASVP implementation has been described in [8]. Miao et al. investigate, beside the basic forms, form features with free-form faces also, with a limitation that they may be produced in 2.5- and 3-axis machining centers. Extraction of geometric information (primitives) is performed using external approach – neutral STEP or IGES data file is exported from CAD model of the part, with B-rep. Faces in ASVP derive different attributes whether they are part of the stock (SS), finished part (MS) or they emerge in some intermediate stage of manufacturing (IS). A general set of forms, issued as a unique combination of SS, MS and IS is then defined as a generation attribute of the feature. Independent forms are directly recognized through pattern matching, while interacting forms have first been parsed along the concave edge loops. System illustration has been given in Fig. 11a.

A similar system has been developed by Dong and Vijayan [70]. The system extracts features from a CAD model using an original technique called ‘‘blank surface – concave edge’’. In this approach the ‘‘overall removable volume’’ (the total material that has to be removed from the blank to produce a finished part) is represented as a set of elementary manufacturing features (parts of volume that are removed in a single tool path). There are numerous alternatives for segmenting the overall removable volume into machinable volumes—the optimal one is selected using the mathematical optimization program. The extraction of geometric features and formation of the part representation for AFR is performed through graphical

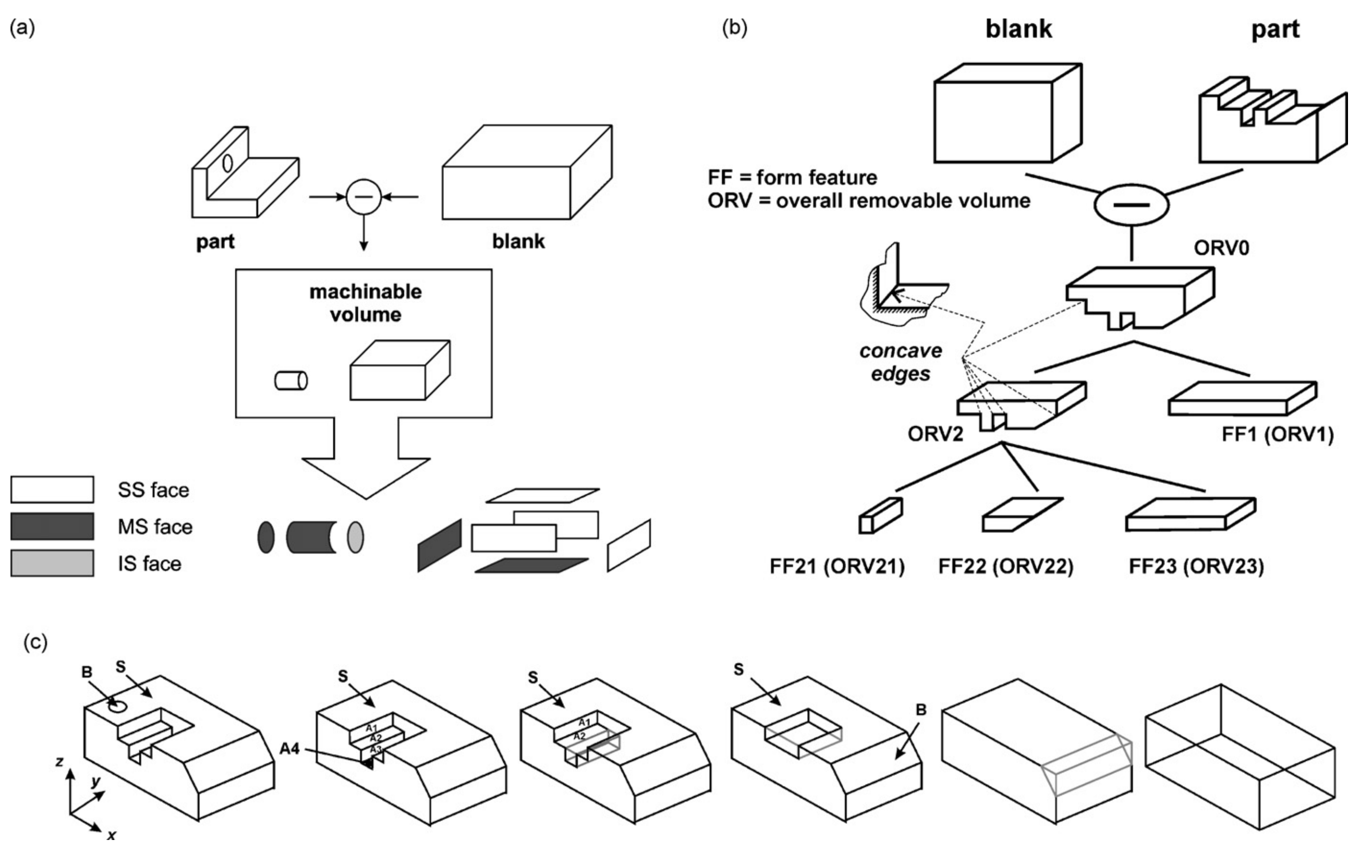


Fig. 11. AFR systems (a) Miao et al. [8]; (b) Dong and Vijayan [70]; (c) Nagaraj and Gurumoorthy [33].

comparison of the part and its blank. The pattern matching process is based on if-then rules. The illustration of the system has been given in Fig. 11b.

In 1990, Wang developed ''backward-growing approach'' [33], in a purpose of more effective treatment of intersecting form feature problem, which can be recognized as particular complex forms or sets of trivial forms. This approach was implemented in the system developed by Nagaraj and Gurumoorthy [33], also based on predefined manufacturing features. The cavity volumes, regarding the most distant outer surface of the part, are defined and, in an iterant process, filled with predefined manufacturing primitives (cuboid, wedge, cylinder, etc.). These primitives are then used for CSG tree formation, in whose structure they can further be reorganized to better suit the selected blank's dimensions. This approach is also specific in that it envisages preformed blanks. The illustration of the system has been given in Fig. 11c.

### 3.6. Cell-based volumetric decomposition approach

In all examples of cell-based (or cellular) decomposition approach, the basic methodology is the same and consists of three steps: (1) the overall removable volume is identified as a difference set between the blank and the finished part; (2) this volume is then decomposed to unit volumes by using the extended boundary faces as cutting planes (cell decomposition); (3) all unit volumes that have common faces or coplanar faces are merged to get maximum cells that can be removed in a single tool path (cell composition).

It is easy to notice the basic problem that characterize this method: even in the case of a simple part a number of cells $\boldsymbol{n}$ created in the step (2) may be very huge, leading to large number of possible feature interpretations in step (3). This problem, addressed as ''the global effect of local geometry'' [6], is generated in the cell decomposition step which extends surfaces or halfspaces associated with the faces of delta volume through the whole part, reaching the areas where machining features would not extend in a reasonable machining sequence. As a consequence, a large number of unnecessary cells are created and the most attention in cell-based methods is paid to dealing with them because they generate multiple interpretations of possible machining features.

Although it had not been originally his idea, Sakurai with his associates was the major contributor to this approach. In earlier version of his system [37], he proposed all multiple interpretations to be generated and then recognized through graph-pattern matching. This system was designed for parts with planar faces and only a limited number of cases of convex curved faces. A large number of possible combinations of cells (up to $\boldsymbol{n!}$) led to an enormous time complexity and, also, not all the interpretations were reasonable from a machining point of view (Fig. 12). In later work [38], he gave detailed and very efficient algorithm for decomposition process and also proposed several heuristic rules to solve the problem of unreasonable compositions, based on convex intermediate volumes and empirical concept of machining the volumes of ''simple shapes with large cutters''. In [39], Sakurai and Dave proposed another algorithm which, unlike previous, allows concave intermediate and final volumes, extending the application of cellular method to objects with all types of curved faces and reducing, but not totally eliminating, the problem of ''complex and awkward'' features. In the most recent research, Woo and Sakurai [40] present the development of an algorithm for scalability of complex parts in order to reduce computational exhaustion and improve applicability of cell-based approach. The delta-volume is recursively bisected into smaller volumes until each one has less than 16 faces. Bisecting planes are chosen to divide volumes in two with similar number of faces. Each of the volumes is then recomposed into maximal volumes which do not have concave edges and are not contained one in another. Then, a search for minimal non-redundant set of maximal volumes is performed. Each volume is examined whether it can be produced in a single operation on a 3-axis machining center—if so, it is recognized as a maximal feature, if not, it is further decomposed. This method is very useful for the most real-world parts (for 2 and 3-axis machining centers are the most numerous in contemporary manufacturing industry), but has no application beyond this limit. Another effort to further improve this method was made by Woo [41]. He attacked the problem of ''the global effect of local geometry'' developing algorithm for ''localized face extension'' which enables faces to be extended only over the concave edges, reducing computational complexity more than 10 times. Further simplification is performed in cell composition stage, through cell collection using ''seed cells'' (which always exist in maximal volumes), significantly reducing the number of possible interpretations. The drawbacks of this approach are inherited from the original method [40] and it also suffers from limitation to objects with features that possess concave edges.One more example of cell-based decomposition method application is a system developed by Tseng and Joshi [5], which can be explained using example of AFR for so-called

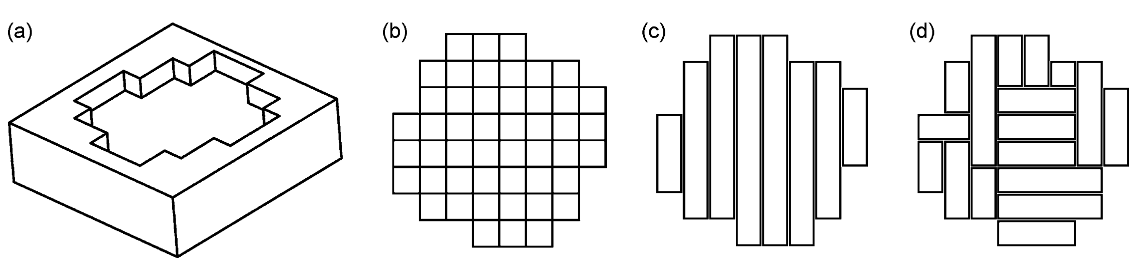


Fig. 12. Multiple interpretations of features in cell decomposition/composition process: (a) part; (b) cell decomposition; (c) a reasonable composition result; (d) an awkward composition result.

mill-turn parts. Input geometrical information (B-rep) is a postprocessed *.txt file in ACIS solid-modeler application protocol interface. First two steps in this method are similar to Sakurai's. In the composition stage the feature volumes are generated by sweeping a boundary face in direction of an adjacent boundary face. The direction depends on predefined type of machining operation: rotational (turning) or prismatic (milling). The methodology of the approach has one additional step, differing for prismatic and rotational structures. For prismatic structures an AAG representation of the cells is made and pattern matching performed, whereas for rotational structures syntactic pattern recognition is performed (Fig. 13). This approach extends application of cell-based methods to more than 2-axis machined parts, but is not applicable to eccentric, asymmetric and complex-curved profiles. Another major drawback of this method is redundancy in pattern recognition—some features may be recognized both as cylindrical and prismatic, depending of sweeping direction.

A recent research, with broader field of application than AFR, has opened a new perspective for cell-based decomposition. A multiple-view feature modeling system for integral product development [42], with a practical solution (SPIFF modeling system) has been a result of a research team from Delft University of Technology, led by Willem Bronsvoort. In its core is a semantic cellular model [43]—a non-manifold geometric model that integrates the contributions from all features in a feature model. It represents geometry as a set of volumetric cells of arbitrary shape that do not geometrically overlap, and lie completely inside or completely outside the shape of a feature. Each cell contains information on every feature that overlap with it, and each cell face contains information on the feature faces that overlap with it. A cell also contains information whether it represents material or void and a cell face whether it has material on both sides, or just one side (feature boundary cell). All this information is stored in ‘‘owner list'' for each cell and cell face; it indicates to which features and feature faces it belongs in each view. The nature of a cell in a view is determined by the features in that view that overlap

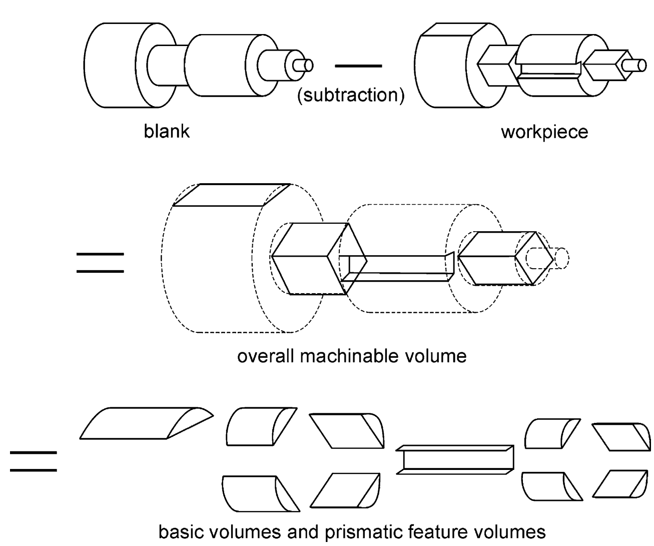


Fig. 13. Cell decomposition method illustration.

with the cell and the dependencies between them [44]—the semantics of feature is well defined and maintained during all modeling operations. The term ‘‘view'' hereby is used to denote different models of product in its development phases.

Cellular representation is designed to be an alternative to classic B-rep models (maybe even more valuable, as it is shown in [45]) because it is history-independent (independent of order of feature creation) and it may store some additional information on features, including some faces which are not on a boundary of the object. Such defined model, using geometric reasoning based on constraint solving, can be converted in specific feature models to be used in different product development phases: conceptual, assembly, part detail and manufacturing planning, and, within the latter, feature recognition. The feature recognition algorithm consists of four phases [42]: shape recognition (the candidates for the shape of a new instance of a feature class are recognized in the cellular model using the shape type and the attach constraints specified in a feature class), parameter determination (the dimensions of the candidate shape are determined from the location of their cell faces, then, an instance of the candidate shape is created and remaining constraints of the feature class are checked. The largest candidate shape satisfying all constraints is the feature shape; if no such shape exists, another feature class is examined), extraction (the feature shape is added to the feature model of the manufacturing view, reducing the inconsistency between the feature models of the part detail and manufacturing), and organization (selection of faces relative to which the feature is positioned, based on specific information from the feature class of the new feature). This approach, thanks to its consistency through different stages of product development and singularity of feature definition, may solve the problems of previous examples of cell-based AFR method application (computational complexity and multiple interpretations), but, due to parametric B-rep based character of the most of contemporary modelers, it will wait for greater popularity until commercial cellular modelers emerge.

### 3.7. Hint-based approach

Hint-based approach has been developed in order to solve the problem of arbitrary interactions of form features and presents a combination of logic approach and delta-volume approach or graph-based approach. Topological, geometrical and heuristic information about the envisaged part are used as the hints of presence of a certain form feature. The largest volumetric feature possible from a hint is then constructed and tested for validity. The method was initiated by Vandenbrande and Requicha [46], in a system called Object Oriented Feature Finder (OOFF), which was designed to deal with intersecting features that, due to immense variety of types of their appearance, had made approaches based on searching the exact patterns of faces, edges and/or vertices unsuitable for the most of practical problems. The authors defined the ‘‘presence rule'' which stated that a machining operation which had produced some feature should have left a trace in the part boundary even when that feature intersected with another. This provoked some other relevant researchers [47] in the field to have given an alternative name to this approach: trace-based. For any feature, a minimal indispensable portion of a feature's boundary may be defined, which, when found in the nominal part geometry, might provide a hint for the potential existence of that feature. In more recent research [48], this system has been improved with the ability to reason about hints generated from various sources, such as direct user input, tolerances and attributes, and design features. The system has been renamed to $IF^2$ (Integrated Incremental Feature Finder) to reflect its ability to combine design-by-features and automatic feature recognition approach into one. Opposite to OOFF, which produced all possible interpretations of feature intersections, in a time-consuming and computationally expensive process, $IF^2$ uses heuristics to generate an interpretation and considers alternatives only on user's demand. The latest version of $IF^2$ system [49] has included the principle to recognize only manufacturing features, consulting the tool database, in order to facilitate sequencing process in an overall CAPP system.

Many other researchers have contributed to enhance the method with completeness of class of features recognized, efficiency of algorithms, use of additional information as hints, and independence from a modeler applied for the part's design. One more example of such a system is given in Meeran et al. [50]. The system focuses on form feature recognition in orthographic and isometric projections of a part, without the use of hidden lines, which cannot be obtained as an input from automated visual inspection systems that this AFR system is aimed for. The input into the system is a graph representation of engineering drawing projections. This representation is first to pass the profile searching stage, which identifies 2D contours in the orthographic views and then it goes through the feature completion stage which establishes the cavity volumes associated with these 2D contours. If the features cannot be established using just orthographic views then the isometric views are examined. The method uses the so-called "divide and interpret" strategy: instead of exhaustive analysis of the whole drawing, the system divides the drawing on several parts, using information obtained from isometric view analysis as hints of presence of a certain form feature.

McCormack and Ibrahim [51] implemented MAAM concept in their researches, adopting external approach for geometric information extraction (neutral data formats—IGES and STEP, or *.dxf) and using hints instead of simple pattern matching to extract the multiple interpretations of the features detected in the part.

Sommerville, Clark and Corney introduced an interesting novel methodology to extract hints from solid models, based on a concept of "light rays" originating from the eyes of a human observer. From the viewpoint, rays are fired and the intersections of rays with different faces of the solid model determine various types of features. This technique, also known as "a viewer-centered approach" can successfully recognize different types of orthogonal features, using the same principle applied in CT (computerized tomographic) scanners in medicine. The algorithm, presented in detail in [52], suffers from several shortcomings, as pointed by the authors themselves: a large number of hints containing many duplicates, small features may be missed by the hint generation process if an inadequate set of viewpoints is chosen, and the process of finding the bounding faces of the feature may give awkward result in cases of features like depression in torus.

### 3.8. Hybrid approach

Gao and Shah [53] in their paper, along with an extensive review of definitions and nomenclature related to different types of graphs developed from AAG, proposed an approach that combines the conventional graph-based recognition with hint-based recognition. The authors have accepted Marefat and Kashyap's [27] concept of virtual links (the edges that, as a result of feature interaction, are not contained in the B-rep of a part) and used them to attribute the extended attributed adjacency graph (EAAG). Their algorithm uses a library of predefined features (steps, blind steps, slots, chamfers, etc.) and a library for compound features, general, through and open pockets and other features that can be generalized through a set of heuristic rules. Each feature is defined in terms of its (EAAG) and other data (feature parameters, access directions, obstacle faces, etc.). The sub-graph components, called minimal condition sub-graphs (MCSG), are generated from the part EAAG, and used as feature hints. After being further processed using extensive geometric reasoning, MCSGs are completed to a recognizable form by restoring their missed links. This system, when applied to parts with planar and cylindrical faces, has proved capable to recognize both non-intersecting (isolated) and interacting features and provide alternative interpretations for each set of interacting features. Nonetheless, its limitation to this class of features only presents a significant shortcoming.

A team of researchers (Corney, Clark, Little, Tuttle) from Heriot-Watt University, Scotland, UK, spent several years to develop a feature recognition system, known as FeatureFinder [54], with an algorithm based on a graph search. At first, the algorithm had been able to interpret the geometry of polyhedral single-sided components but, it was later [55,56] extended to handle multi-sided components requiring more than one machining direction, depressions and protrusions bounded by cylindrical faces (as well as planar faces) and "open" features as through slots. The latest version of FeatureFinder has been capable of identifying a variety of features on a wide range of machined components. The system has been designed to be used within a solids machining package and identifies features from a specified tool approach direction.

In four distinct steps, the algorithm produces a set of manufacturing feature volumes, each of which represents the material to be removed by a manufacturing operation. The first step represents the selection of the tool approach (aspect) direction by a process plan engineer. Only one tool approach direction is considered at a time. Secondly, a closed chain of paths which travel across each vertical face of the component is generated ("vertical" face is the one that lies in a plane parallel to approach direction). Then, for each machining direction, the paths are linked to form closed cycles representing the 2D profile of 2D feature volumes. In the last step, a user interaction is needed again to select which cycle is to be used to create the feature volume. Once a valid cycle has been generated, the 2D profile is swept to the height of the cycle, manually defined by a user. Only planar entities can be considered for sweeping in this technique for volume construction and even the presence of drafts may prevent its successful application. For multi-sided components, the user has to observe which paths are approachable (''visible'') in the given direction.

Human intervention, demanded to provide the tool approach direction, cycle selection and visibility information, should be considered as a major drawback, because it reduces the level of automation of feature recognition process; but it also may be regarded as an advantage, for the volumes identified in such way share a common set-up which would be useful in subsequent stages of process planning, such as sequencing the manufacturing operations. Although primarily graph-based, this approach is in this review classified as a hybrid one, because of its multi-step reasoning character and volume construction driven by tools accessibility, which is the attribute of volumetric approaches, and human intervention, which is widely promoted in hint-based approaches.

Ye et al. [57] presented the AFR system based on face-edge EAAG, aimed to recognize isolated and interacting undercut features from moulded parts planar, quadric and free-form surfaces. It takes face properties and parting lines as hints for recognition of undercut sets. To deal with the face properties of free-form surfaces a convex-hull algorithm has been developed. This system is supported with an extensive set of heuristic rules for hint generation and has proved to be successful in this limited area of application.

An attempt to develop more general system has recently been presented in [58]. This method uses an AAG which is decomposed to limit and organize the search space for feature hints. Hints, in sub-graph forms, are extracted from the decomposed graph components. They indicate whether the feature is 2.5D, floorless or 3D. To reduce the product model complexity while extracting features, a method to remove fillets existing in the boundary of a 2.5D feature is also proposed. The hints are extracted in a graph form, but the feature is completed geometrically, using three geometric completion algorithms (base and profile completion for 2.5D features and 3D-volume generation algorithm). The base completion and profile completion algorithms generate maximal volumes for features whereas the 3D volume generation algorithm extracts 3D portions of the part. This hybrid system, beside graph and hint based combination, adds the volumetric component, completing feature's geometry instead of graph components in the process of restoring of missing links. The authors have described examples of successful application on several test-parts from NIST design repository, but as any other system based on hints, it also requires user intervention and seems to be verbose.

There are several examples of hybrid AFR systems which combine characteristics of graph-based approach and convex-hull volumetric decomposition. One of them is the system described in [59], which uses a modified attributed adjacency graph (AAG) to facilitate the representation and recognition of isolated or interacting depression features. The modification of AAG is performed by adding the ''reference face'' (determined on the basis of convex hull concept) into the AAG, providing more clues in the process of feature detection and recognition. Two general feature types, namely depression and protrusion features, are identified by the reference face. The basic features such as slots, pockets and bosses are represented by the modified AAG (called RAAG by the authors) and the other features that remain unrecognized are regarded as interacting features. The recognition of features, also based on the concept of virtual links, is enabled by reconstructing the necessary boundary faces that might have been lost due to feature interaction. The extraction of features is simplified by adding the cavity volumes of the recognized features back to the original volume of the object. This system has shown a significant capability of dealing with interacting features, but only with those predefined in the feature library. That's why it needs redesign of its pattern recognition function (the third task of AFR) and transfer towards the use of AI techniques.

The other example of a hybrid between graph-based and convex-hull approach is a system developed by Sundararajan and Wright [60]. It introduces so-called ''open edge'' concept to promote the information about feature adjacency. The system is able to treat prismatic parts and even a limited class of free-form features, but only those machinable from six basic directions along coordinate axes. Free-form features are defined similar to the 2.5D features as comprising a planar contour, but substituting a bottom free-form surface for the depth. Covering faces, defined as projection of the free-form surface on the faces of the bounding box of the surface, are used as equivalent planar faces for performing the recursive descent. The relationship between the free-form feature and other neighboring features is determined through common open-edge identification. The drawbacks of the system, beside the restriction regarding machining directions, include the problem of recognition of fillet as a free-form feature.

The work of Yong Se Kim has already been described in detail in Section 3.5. In more recent research [61,62] Kim adopts a hybrid method, combining logic approach with ASVP to improve AFR results in specific application domains. The logic (face pattern based) approach has been used for recognition of isolated features, whereas convex-hull volumetric decomposition has been applied for recognition of interacting features.

In his more recent work, Subrahmanyam also introduces hints into the cell-based volume decomposition method [63]. Improved, heuristic-based volume decomposition method, by removing possible isolated machining features and slicing edges in an early stage of recognition process, reduces the search space and the complexity of the combinatorial problem. This system is strongly oriented to manufacturability of recognized features and, being able to generate alternative solutions, proves to be flexible and adaptable. However, the algorithm is not able to recognize chamfers and fillets as high-level features. The other drawback is that this system can work with parts with single set-ups only.

If systems with rule-based pattern recognition have any future at all, then it lies in hybrid approaches. They combine the advantages of constituting conventional methods and there are many examples of their successful applications, but only for limited classes of features they are primarily designed for. The lack of successful hybrid algorithms generalization for broader range of feature classes presents the major drawback of this set of approaches for automated feature recognition.

## 4. Conclusion

AFR is the first and the most important step in the process of translation of CAD information into some instructions appropriate for manufacturing. To eliminate a need for human engagement in feature recognition process is essential for a fully automated CAPP system development. The advantages of AFR compared to feature based design are significant time and human resources saving, as well as insurance of desired part functionality without being limited in design creativity by the possibilities of the predefined form feature library. However, in spite of large research efforts, contemporary AFR systems still suffer from many disadvantages [64]: (i) complexity of the recognition algorithms, especially in the case of intersecting features—there is an immense problem in determination of the set of features for which production must be explicitly planned and which features may be collaterally produced by producing certain others; (ii) the domain of recognized features is quite limited—the most of contemporary recognition systems mainly deal with orthogonal features, but with little attention paid to nonorthogonal and arbitrary features; (iii) the manufacturing information attached to the recognized feature is not rich enough to facilitate the determination of the subsequent production plan, etc.

There are some additional remarks on current status of AFR techniques with rule-based pattern recognition that we want to emphasize in the conclusion:

- There is no general solution for the problem of multiple interpretations of part feature models;
- The most of the research is done in the domain of machining, though there are several recent reports of more or less successful implementation of AFR techniques in other manufacturing domains, such as sheet metal stamping, metal forming, moulding and casting;
- In order to enable effective application of recognized features in downstream CAPP modules, or in inspection and assembly process planning, AFR systems should be capable of recognizing dimension and geometric tolerances along with other feature attributes;
- Although an immense effort has been placed in theoretical research in this field there is little evidence of practical implementation of the results in successful commercial software for AFR, like KBM [65] or FeatureCAM [66].

Three major problems remain unsolved in contemporary AFR systems with rule-based pattern recognition:

- How to determine sufficient number of templates in feature pattern repository;
- How to ensure their validity regarding the fact that their characterization is heuristic;
- How to deal with the problem of interacting features in a universal way?

The existing techniques for overcoming these problems have been classified in a pedantic way by Wu and Liu [67] in a 5 groups: (i) generic representation schemes for features; (ii) recognizers with learning capability; (iii) missing information recovery; (iv) feature-based systems mixed with B-rep; and (v) other works. However, from all the reasons mentioned above, the overall algorithm that would provide fully automated feature recognition process still does not exist. We believe that novel researches in AFR field should focus in finding more efficient algorithms for extraction of necessary geometric information from a CAD model and knowledge acquisition in form pattern database, through implementation of artificial neural networks and other advanced artificial intelligence techniques.

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