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Automated Rule-based System for Opitz Feature Recognition and Code Generation from STEP

Leila Zehtaban and Dieter Roller

University of Stuttgart, Germany

ABSTRACT
This paper presents a framework for an automatic classification of product shape information aimed for design retrieval and know-how transfer in the design-by-feature using Automated Feature Recognition (AFR) approach. The proposed rule-based method uses an extendable well-known coding system, so called Opitz Coding System applied in Computer Aided Manufacturing (CAM) for grouping part families. The proposed method applies the advantages of know-how transfer between two distinct phases of product development, i.e. CAD and CAM. Many researches already aimed to efficiently integrate computer aided design, analysis and manufacturing for optimizing concepts such as product life cycle and computer aided process planning. However, most of these researches focus on optimization of the downstream process, i.e. from the low-level entities of CAD such as line and points to the high-level manufacturing entities such as chamfers or threads. On the contrary, this paper introduces a new approach for design optimization by considering CAM entities in the first stage of product development.

KEYWORDS
Automatic Feature Recognition (AFR); Rule-based system; Opitz Coding System; STEP

1. Introduction

Reducing product development costs while keeping high quality for a product is a critical concern to any manufacturing company. Among all the facts which emphasize on importance of the early design decision phase in the product's final cost, there are two major studies and evidences as follows. The first types of researches refer to the design activity distribution and it's relating cost. Based on Ullman [26] more than 75% of engineering design activities contains reuse of previous design knowledge to address a new design problem. Or as A.D. Little stated: "Up to 80% of the work done in an engineering department is identical or very similar to work done previously" [4]. The second evidence refers to the cost of changes in the first stage of design which is highly economical in comparison with later stages. Consequently, there have been several researches attempt to resolve this challenge applying various approaches such as concurrent engineering, agile manufacturing or CAD/ CAM integration methods [1].

One of the major methods to optimize design decisions and ultimately optimizing the design in the early design phase is to provide designer a multidisciplinary knowledge based infrastructure for categorization of product data. In this regard, standardization of such a multidisciplinary data is the foremost phase of a systematic product data management.

An interesting method of part data standardization is Group Technology (GT) originated for manufacturing feature recognition. The process of manufacturing part feature recognition as well as the part manufacturing processes is typically described in variant Computer-Aided Process Planning (CAPP). In the current research, the manufacturing classification system has been applied for the classification of geometrical parts in the early design phase of a product as a technology transfer, Fig. 1. Among all the various models of shape classification and representation [13], group technology has been selected for this research based on two reasons. The first reason refers to the flexibility potential of GT, since it can be extended for a comprehensive product part data representation which none of the well-known models of shape representation such as graph-based [9,10],[15] harmonic-based [14],[28] statistical-based [2],[19] 3D object recognition-based [7],[22] or Invariant/descriptor-based [6],[27] has. The second reason is the extensive application of GT in the manufacturing industry for classification of part families. Group technology uniquely identifies its part-families with the use of codes. A code is usually a series of alphanumeric characters of a predefined length. They are

CONTACT Leila Zehtaban zehtaban@informatik.uni-stuttgart.de

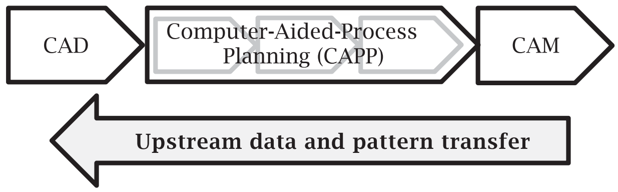

Figure 1. Technology transfer in integrated design and manufacturing engineering.

listed in succession with or without delimiters depending on what each character signifies. A code's characters may represent certain properties common to all products/parts in the part-family. Typical GT coding systems comprises of Opitz coding system (13 digits), MICLASS (12 digits), KK3 system (21 digits) and DCLASS (8 digits). For this research, Opitz Coding System has been selected based on the discussion in the following section.

The proposed methodology comprises of two main phases: first phase, geometrical feature extraction from STEP, and second phase is Opitz code construction. Nonetheless, these two phases are tightly associated to each other. Otherwise stated; the geometrical feature extraction algorithm is specifically tailored for recognizing the features defined by Opitz codes for rotational parts as well as prismatic or non-rotational parts. To accomplish the objectives, a rule-based system has been proposed and developed to extract the Opitz features correctly from STEP file.

Based on the above introduction, the contents of the current paper are divided into two main sections: the first section includes Opitz feature extraction from STEP file as well as the presentation and discussion of the Opitz features. In the second section, the fundamentals of rule-based systems are explained and the proposed rule-based system is presented.

2. Opitz Coding System

Between different methods of part classification systems in GT, Opitz coding system [18] is one of the most well-known and widely applied approaches. Initially, Opitz coding system recognizes manufacturing features and lists them in a predefined order of digits as a code. Around 300 geometrical and topological single features are recognized as individual Opitz features to be settled in digits. Moreover; with different possibilities of combinations of single features in a code around 30,000 part features could be recognized. In this paper, for constructing Opitz code two methods have been applied; Automatic Feature Recognition (AFR) as well as rule-based system (explained in the next sections).

An Opitz code is composed of 14 digits divided by three categories. The first category, 1st to 5th digit, is called "form code" dedicated for design attributes including gemetrical and topological information (Fig 2). The second category from 6th to 10th digit is supplementary code used for manufacturing attributes. And the last category digits 11th to 14th are secondary code for production operation type and sequence. Opitz has 5 main digits in which each digit can get numbers from 0–9. It means all together, there are 50 single features recognized in this system only in the form code. However, several combinations of these features provide 10*10*10*10*10 variations for a single part which can be identified by Opitz code.

Opitz code provides a basic framework for understanding the classification and coding process. Furthermore, it can be applied to machined parts, non-machined parts and purchased parts as it considers both design and manufacturing information.

In the context of PLM, the variant applications of Opitz coding system can be found in [25]:

- Design: variety reduction, recognition of repeat or similar parts;
- Standards: standard components easily identified, uniformity of characteristics;
- Production planning: use of repeat, grouping parts requiring same machines, use of standard times;
- Production control: suitability for data processing;
- Production: parts family manufacture;
- Equipment: adapting the machine tool to the work pieces required.

In the first category of Opitz code, correspondingly in the form code, the first digit is the decisive digit which distinguishes between rotational and non-rotational parts. Furthermore, this digit calculates a dimensional ratio to evaluate the geometry of the shape. For rotational parts the code uses the length (L) and the diameter (D) of the components in decreasing order of magnitude. The second digit stands for external shapes and relevant forms, these features are recognized as stepped, conical or straight contours. Threads and grooves are also important. The third digit is for internal shapes, features are solid, bored, straight or bored in a stepped diameter, threads and grooves are integral parts. The fourth digit is for the surface plane machining, such as internal or external curved surfaces, slots and splines. And finally the fifth digit is for auxiliary holes and gear teeth.

In the category of supplementary code, there are four digits in which the first one is for diameter or length of the work piece, the second one is for material used, the third one is for raw materials like round bar, sheet metal,

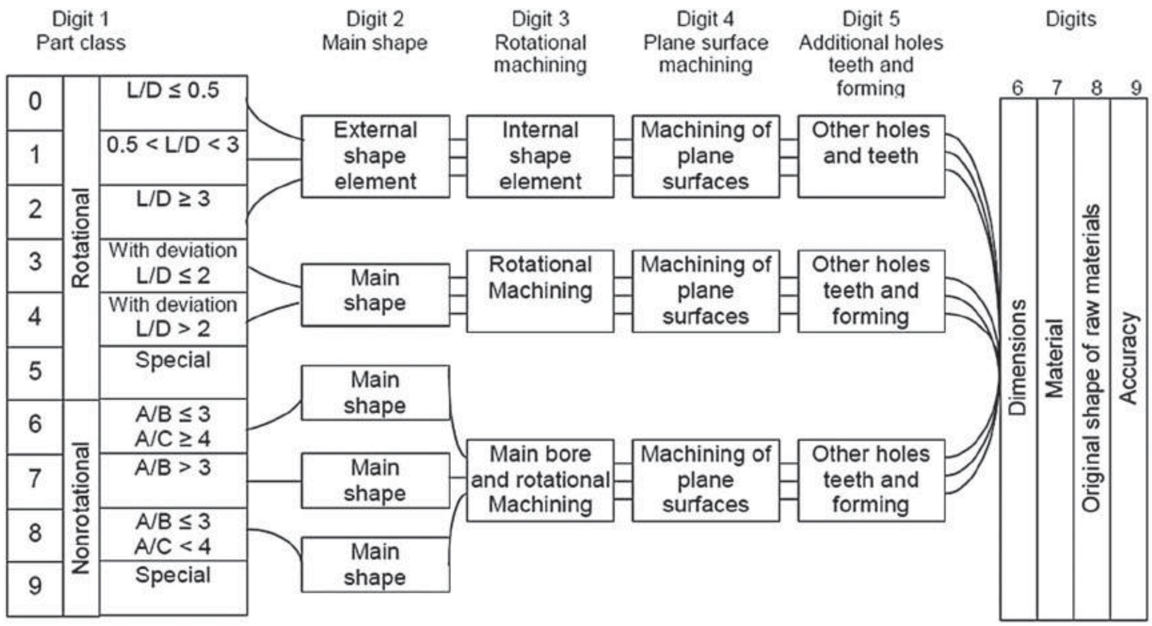

Figure 2. Opitz Coding System [17].

casting or tubing and the fourth digit is for the accuracy of the work piece.

Among three types of GT including hierarchical structure (monocode), attribute codes (polycodes) and hybrid model [23], Opitz code follows the monocode structure. In monocode structure each digit (or position) in the code represents a feature/sub-group with a hierarchical structure, Fig. 3.

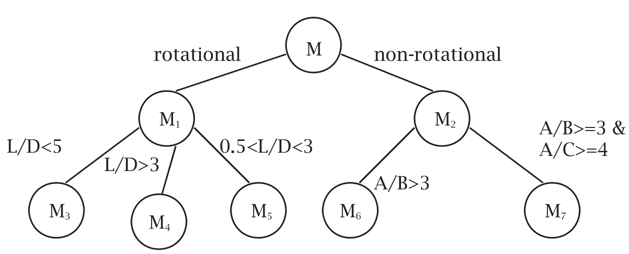

Figure 3. Monocode structure for a part of the first digit of Opitz code. The "L" refers to the length and the "D" refers to its diameter of rotational parts. The "A", "B", and "C" refer to the length, width, and height of the non-rotational part respectively.

In Fig. 3 the first digit divides the parts in two groups, rotational and non-rotational forms. There are more calculations and consequently categorization which decides for other features such as flat, cubic and long components. In this sense, each subsequent digit is qualified by the preceding digits (or, in an object-oriented sense, each subsequent digit inherits the properties of the previous digits).

2.1. Opitz coding system: advantages and disadvantages

Opitz coding system as a method of GT benefits from the advantages of classification in engineering design such as design reduction of similar parts and drafting errors, easy retrieval of similar parts, as well as having an overview on parts expenses and manufacturing limitations. Moreover, benefitting from its representation form as a code and having the capability of code extension increases the level of information customization. Additionally in original Opitz coding system some of the digits are preserved for the special features.

Opitz coding system is a public domain and non-proprietary method which has been highly applied in industry in comparison to the other methods of GT such as KK3, DCLASS and MICLASS [25]. Some of these codes such as KK3 contain more complete information in comparison to Opitz code which is merely focused on the manufacturing aspects.

Few disadvantages have been mentioned for GT coding system [5] regarding the coding generation process, connection between data and code as well as a generalized overall part description. To overcome these challenges in the current research, AFR method has been used to generate GT code automatically. Furthermore, in the database all information about a part is saved together in the database to facilitate the retrieval of information about a part including CAD model, extra engineering notes as well as the Opitz code. However, the last challenge refers to classification aspect of GT code. This problem could be reduced by utilizing all digits of

Opitz code, i.e. 13 digits or adding extra digits to maximize the variations in a dynamic model. In addition, GT codes including Opitz coding system are applied merely for part classification not assemblies. In the next section, an overview on the automatic feature recognition techniques is presented.

3. Automatic Feature Recognition (AFR) Techniques

The significant role of feature recognition in computer aided mechanical design has been researched for decades [11],[21],[24]. In respect to automatization of feature recognition, several methods have been developed for automatic feature recognition. Babic et al. [3] published a comprehensive review and classification on automated feature recognition techniques. Based on their classification, there are two main categories for form feature extraction; geometric feature extraction and form feature identification. This classification is autonomous of CAD file format whether B-Rep, STEP, wire frame, etc. For identification and matching of the predefined features in a database, logical rules or artificial neural networks are applied. Due to the noble achievement of expert systems, rule-based system has been one of the most successful techniques for feature recognition. It analyzes and represents the pattern's characteristics of features as rules which are stored in the knowledge base of an AFR system. Several researches have studied the application of the rule-based method for feature recognition [8],[12],[16]. According to Babic et al, rule-based systems are more robust in handling feature recognition and can identify more components than syntactic methods; however, lack of clear rule definitions and the need to cover all possible and conceivable features makes them inflexible. This is mainly because rule-based systems do not acquire new knowledge once they have been fitted with their initial set of rules.

Rule-based systems are extremely popular in the data mining field, and there exist multiple variants of such systems. These include, but are not limited to, decision trees, IF-THEN classification and association rules. While some of these techniques are mostly descriptive, they can be used to validate and infer new rules in a certain system, given enough data.

Van der Velden [27] developed a framework for automatically extracting engineering features from neutral STEP models to be used in downstream processes including, but not limited to, analysis (CAE systems) and manufacturing process planning (CAM systems). The system focuses on the important design consideration which effects on efficiency and accuracy of the feature recognition. These elements include identification, capturing, organization and implementation of feature recognition rules within the AFR system.

The proposed methodology by Van der Velden has shown good results in recognition and extraction of engineering features from geometrical models.

In this regard and for the means of Opitz feature extraction, we have developed an automatic rule-based system which follows the steps of the Van der Velden method partially. New details are added and unnecessary aspects were ignored. Section 4 explains the entire steps and methodology of the proposed method.

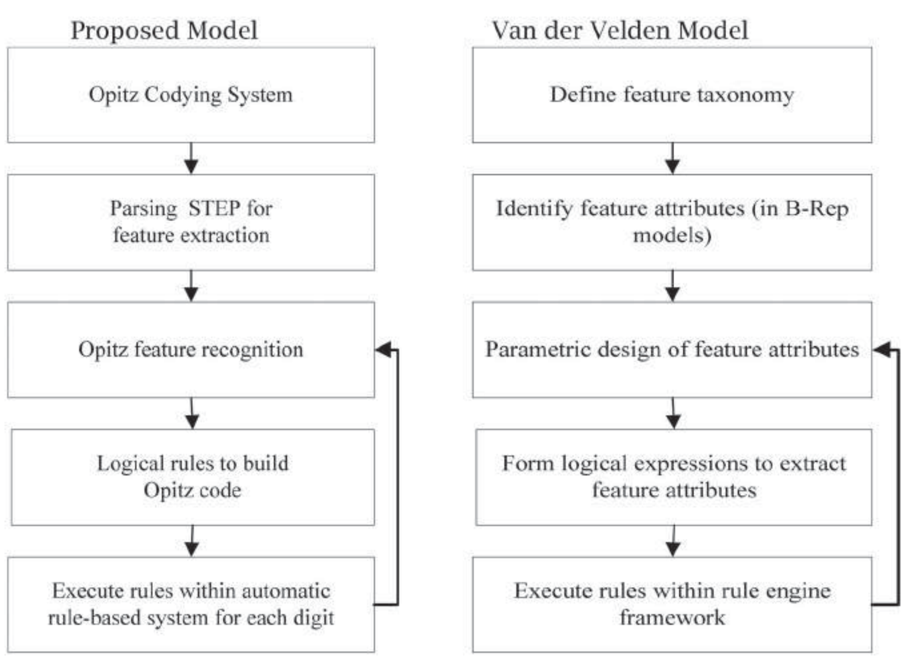

Figure 4. Comparison of the Van der Velden model [27] with the proposed model.

Fig. 4 demonstrates the five steps process for structuring feature recognition rules in comparison with the proposed method is presented.

4. The Proposed Methodology: from STEP to Opitz code

In order to obtain an Opitz code from a STEP file, there are three main phases, Fig. 5. The first phase deals with STEP file with parsing, reading and analyzing the required data for Opitz features. The output of this phase is a neutral data sufficient to extract Opitz features. In case CAD files are saved in other formats such as IGES rather than STEP, this step can be extra developed in such to produce the same output while rest of the phases would be identical. The reason for choosing STEP file format is mainly due to being a standard format that can be used across multiple CAD software applications. Due to the textual nature of STEP files, they were treated as such and not special treatment was required in opening and reading the files. Once the file was read, the components would then be stored in a hashmap, and entities would be created accordingly. The entities would also form a graph-like structure due to the nature of their interconnection, and to keep track of their topology

The second phase utilizes the neutral data assisted by positioning stages. Positioning stages are individually defined for each Opitz features. Three examples of positioning stages are presented in the appendix of this paper. These examples contain two cases for identifying a "main bore" and a "chamfer" as non-rotational features. For rotational part a "rotational component stepped at both ends with no shape element feature" has been presented and explained. The output of this phase is a number to fulfill a single digit of Opitz code.

The third phase applies a rule-based system to the solo digits to construct the complete code. There is a continuous cooperation between phase two and phase three until the code is completed. The rule-based system comprises of three main categories; R1, R2 and R3 presented in the next section. R1 category comprises of the geometrical rules mainly based on the first digit of Opitz coding system for rotational as well as the non-rotational parts. R2 category presents operations with plane surfaces parallel to Y-plan and R3 category was considered for the operations with plane surfaces parallel to Z-plane.

The above diagram, Fig. 6 shows the decision tree to determine the second digit of the Opitz code when the first digit is less than 3. Of this tree, the screwthread, taper and operating thread inquiries needed to be designed, and later implemented. The rule evaluation takes place in a forward-chaining manner, first inquiring about the shape's smoothness, and then based on the result, moves to the appropriate sub-tree, and so forth.

The second digit varies according to the value of the first digit of the Opitz code. This is due to its hierarchical nature. There are multiple subtrees for the second digit that depend on the value of the first digit. These subtrees are arranged accordingly:

- when the first digit is less than 3,
- when the first digit is greater than 2 but less than 5,
- when the first digit is equal to 6,
- when the first digit is equal to 7,
- and when the first digit is equal to 8.

In the first case, the external shape and the external shape elements are described. In the other cases, the overall shape of the part is described.

The Opitz code defines the digits 2 and 3 (in the second position when the first position < 3) for both smooth surfaces, as well as those stepped to one end.

The first five digits of Opitz code can be classified based on the input from the STEP file; however, it is

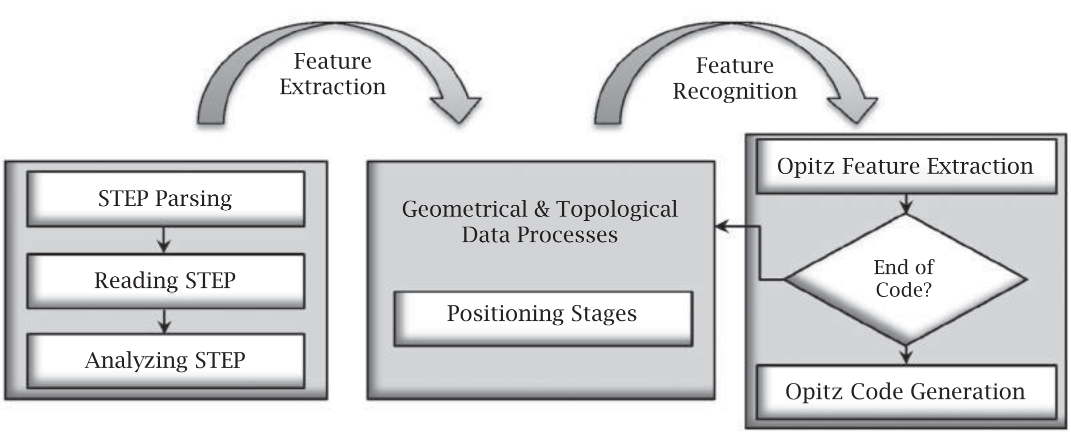

Figure 5. The proposed Opitz feature extraction and recognition framework.

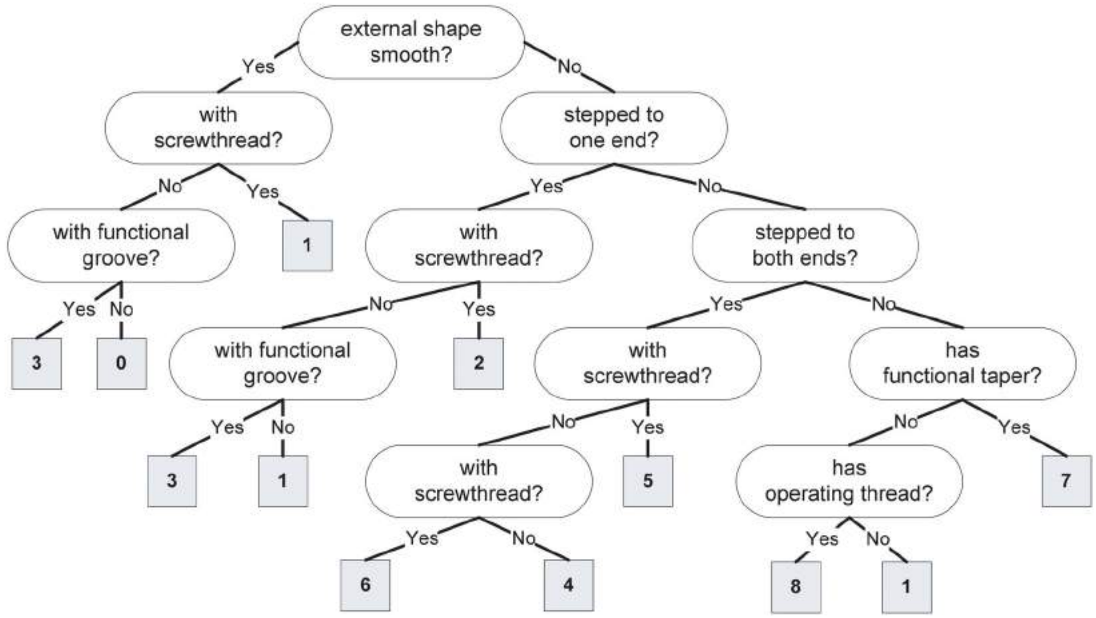

Figure 6. Opitz Code Tree for the second digit (1st < 3).

different for the rest of the code. There is no information in the STEP file regarding material, or even accuracy for that matter. So, it was concluded that they should be entered by the user himself. As for the last digit, which pertains to accuracy, a novel approach was employed. The recognition process must be made flexible enough to accommodate the user, and sometimes, user errors. A standard level of flexibility is set for each feature (or digit), all the while giving the user the option to override that level.

In general the following rules for features recognition have been proposed:

R1. Part dimension measures extraction (length, width, height)

R1.1 Flat non rotational part identified (length / width <= 3 and length / height >= 4)
R1.2 Cubic non rotational part identified (length / width <= 3 and length / height < 4)
R1.3 Long non rotational part identified (length / width > 3)
R1.4 Rotational part (1st digit of Opitz code = 0): length / diameter <= 0.5
R1.5 Rotational part (1st digit of Opitz code = 1): 0.5 < length / diameter < 3
R1.6 Rotational part (1st digit of Opitz code = 2): length / diameter >= 3

R2. Operations with plane surfaces parallel to Y-plane.

R2 rule set can be presented as a tree depicted in Fig. 7. All rules within current tree are hierarchy dependent, starting from the root node going to its child nodes. For example, to identify a ring machining on some non-rotational part, the chain of rules R2 -> R2.1 -> R2.1.2 -> R2.1.2.3 -> R2.1.2.3.1 within given tree should be satisfied, Fig 7.

R3. Operations with plane surfaces parallel to Z-plane.

R3 rule set can also be presented as a tree illustrated in Fig. 8. All rules within this tree are hierarchy dependent, starting from the root node going to its child nodes. For instance, to identify a long non-rotational part that has a rectangle as a cross section, the following chain of rules R3 -> R3.1 -> R3.1.1 -> R3.1.1.1 within given tree should be satisfied, Fig 8.

The reason for considering only Y-plane and Z-plane is that for rotational parts, such as a cylinder, they would most likely be perpendicular to either the Y- or Z- axes and that would be enough. This assumption can also be generalized to non-rotating parts as well, however, in this case the surfaces would exist, but their features could be extrapolated from the other planes (saves effort, but does not result in clear code). In addition, the third type of surfaces may not be parallel to the X-axis, making the rule somewhat inefficient.

5. Hierarchical Representation of the Developed Rules

The following figures, Fig. 7 as well as Fig. 8, present the rule sets to identify a specific Opitz feature. Fig. 7 is dedicated for the rule set R2 which pertain to the operations with plane surfaces parallel to Y-plane. Furthermore Fig. 8 defines the rule set R3 as well as the sequences to reach and identify are the operations with plane surfaces parallel to Y-plane.

6. Discussion

In recent years, there are commercial softwares such as FeatureWorks which provide automated feature recognition abilities as well. However; FeatureWorks is an image-based feature recognition, in comparison with the proposed approach which is a code-based solution. The key advantage of a code-based approach which could surpass an image-based is the capability of containing and transferring additional information of a part rather than focusing merely on topological and geometrical information.

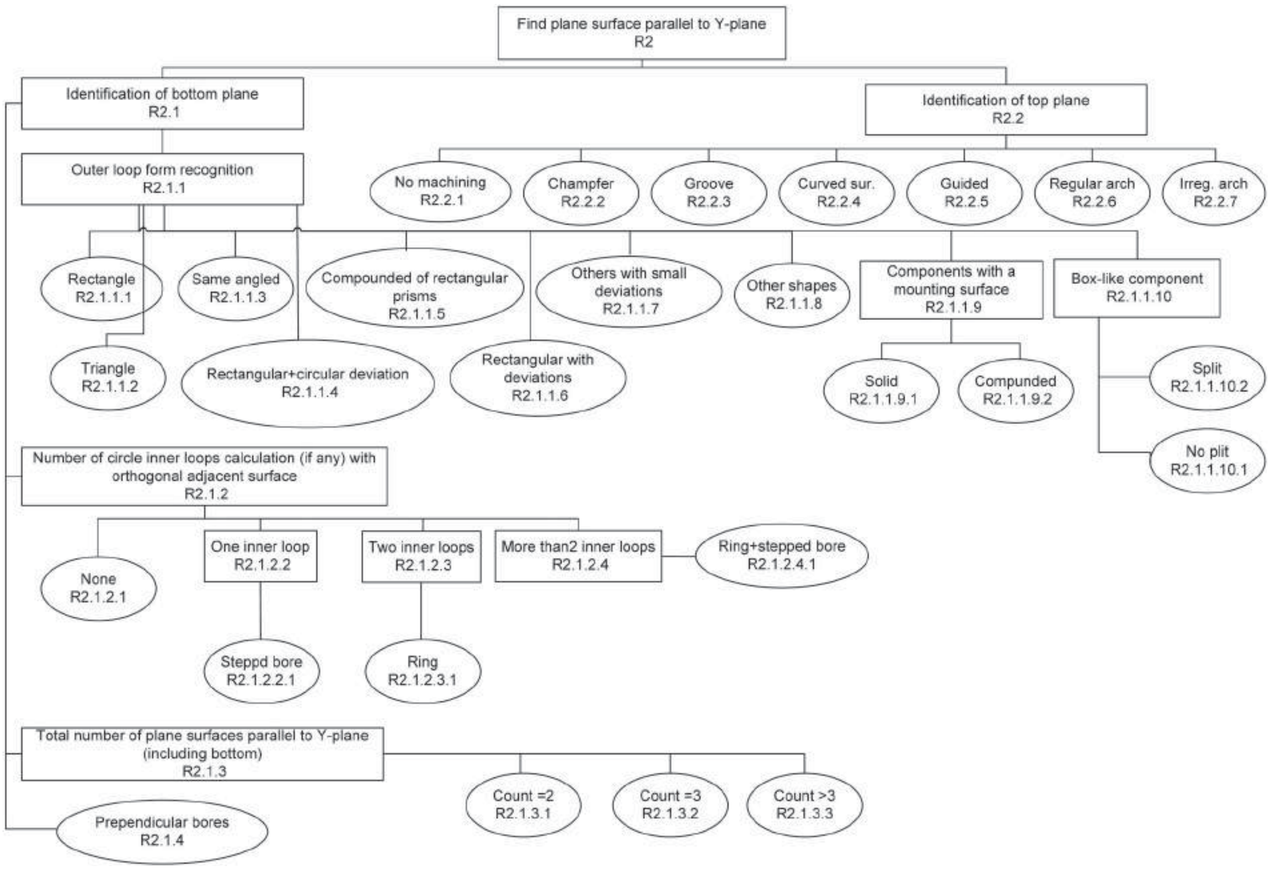

Figure 7. Rules for Opitz feature recognition of surfaces parallel to Y-plane for STEP-based data.

The feature recognition in the proposed approach has been limited to the manufacturing features domain. Nonetheless, this is one of the intentional achievements of the approach as this classification can be applied later in CAPP.

The implementation was a proof of concept in order to define, extract and complete the Opitz digits. The system has been tested with two types of data. First some online sources of various manufacturers were investigated with this method in order to find real production CAD-models covering an entire area of different product features. Additionally, some CAD models were created and tested too. After analysis of the implemented methodology the following problems were formulated. First problem is related to Opitz code and it happens when a groove is not found and an upper curved machining is identified for non-rotational parts. For this case Opitz code system gives only classification for groove or upper machining, not for both features at the same time. That is why the algorithm must select one of them ignoring the other one. Second, for non-rotational parts there are 3 Opitz code groups of plane surface machining: one plane surface, stepped plane surface, stepped surface vertically inclined and/or opposed (4th digit of Opitz code = 2, 3 and 4 respectively). These groups differ in the methods of machining, having in the result the same part shape. It means that for features of these 3 groups the algorithm has only shape geometry, not machining method; so it is impossible to relate a detail to the strict class, and by default there is a relation to the class of 4th digit Opitz code = 2. Third, there are problems with cylindrical surfaces counting for rotational parts. This is a programmatic error, not methodological. And finally few problems with stepped bores and grooves identification were found. Along with the identified problems which were evaluated as minor, the basic implemented algorithms as well as the developed functionality witness's high-quality outcome result with a proved ability to recognize an entire set of part features for non-rotational long, flat, cubic and rotational parts having a proper accordance to Opitz code classification system.

Apart from this, the main problem of using Opitz code for classification is that a part can be converted to a unique code, but an Opitz code does not necessarily refers to a specific part [29]. As Fig 9. Presents there is an identical Opitz code for two different parts. Consequently the related equation is not an injective function, eqn. 6.1. To individualize it further, there should be an injective function for the given domain. To summarize, the current system must use an injective function to reach the

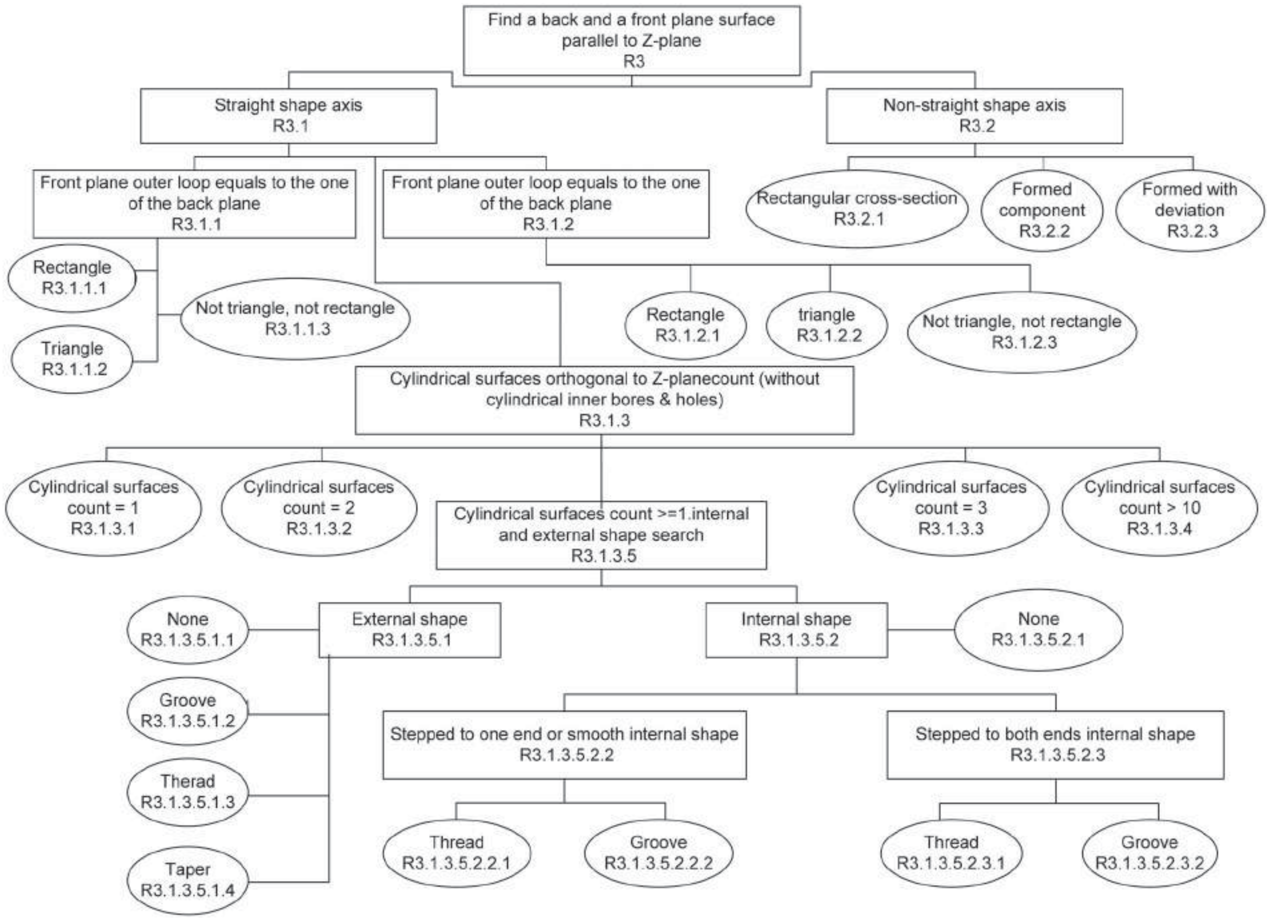

Figure 8. Rules for Opitz feature recognition of surfaces parallel to Z-plane for STEP-based data.

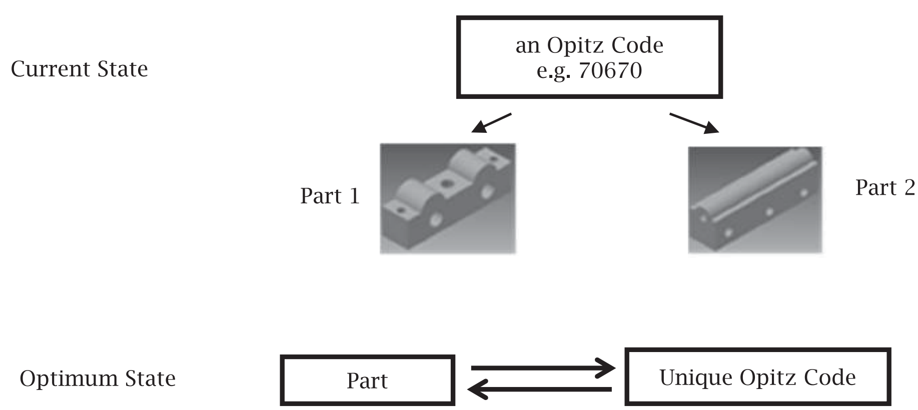

Figure 9. Challenge of the Opitz code uniqueness.

ideal solution.

$$\text{Injective function } \forall a,\ b \in A,\ f(a) = f(b) \Rightarrow a = b$$
$$\forall a,\ b \in A,\ f(a) \neq f(b) \Rightarrow a \neq (b) \quad (6.1)$$

7. Conclusion

The main objective of this research was to develop a method that enables product feature recognition and extraction from some standardized part shape format in conformity with Opitz Code Classification System. To achieve this goal, a classification system based on Opitz code for rotational and non-rotational parts was developed.

Group Technology (GT) as a classification method that implies feature recognition was evaluated and Opitz code as a method of GT was implemented for this research.

The developed system was implemented by means of Java programming language; STEP representation format was used to reflect particularly part shape geometry and topology. After a STEP file is loaded to the system, feature extraction process starts together with generation of Opitz code signature. This process presents a "classification" while having the Opitz code as a shape signature and as the final result of this model implies a predefined group according to Group Technology. A graphical user interface has been also implemented to allow user to choose preferred STEP file and to see feature recognition progress with informative notifications and the out coming Opitz signature.

During evaluation a few minor problems regarding Opitz code were identified. This includes errors caused by lack of manufacturing data. The reason is that Opitz classification has groupings by a number of machining data which is not supported by STEP shape representations. This problem is overcome by means of programmed code refinement and the extension of STEP presentation to include required manufacturing data.

ORCID

Leila Zehtaban http://orcid.org/0000-0003-1954-684X
Dieter Roller http://orcid.org/0000-0002-2438-5676

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Appendix

Positioning Stages for Opitz Feature Extraction

In this section, some of the positioning stages dedicated for Opitz feature recognition are presented with examples. These stages provide all information required for the next phase, i.e. constructing the Opitz code. The stages are designed to obtain geometrical as well as topological information of the main Opitz features.

To illustrate further, three features and their positional stages are presented in the following. These features include main bore, chamfer and identification of the rotational component stepped to both ends with no shape element.

Example 1: main bore

In order to determine the geometry of this feature, the following stages are defined, Fig 10:

1. Bottom surface should be found which is plane (not cylindrical or conical surface) and parallel to Y-plane
2. Bottom surface should have one inner loop which is a circle
3. Adjacent surface (that is a cylinder) to this inner loop should be orthogonal to the surface of current inner loop.

Example 2: chamfer

The following stages are applied, Fig. 11.

1. Top surface should be found which is plane (not cylindrical or conical surface) and parallel to Y-plane
2. All adjacent surfaces to top plane should have the same angle between the normal of the current surface and the Y-oriented normal (0, 1, 0)

Example 3: identification of the rotational component stepped at both ends with no shape element feature

The applied rules to distinguish this feature include, Fig. 12:

1. Front and back surfaces should be found which are plane (not cylindrical or conical surface) and parallel to Z-plane having the maximal and minimal z-coordinates within current shape respectively
2. There are 3 cylindrical surfaces should be identified that are orthogonal to the plane of the back surface

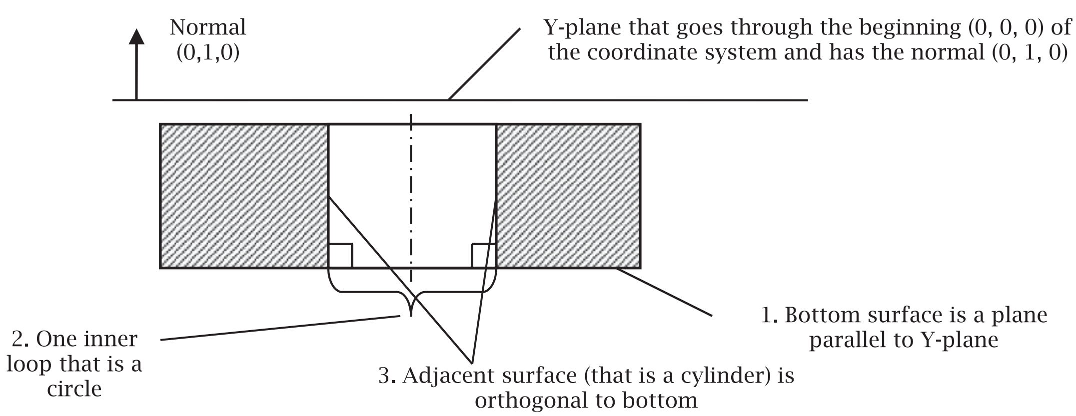

Figure 10. Cross section by Z-plane through a part with one main bore.

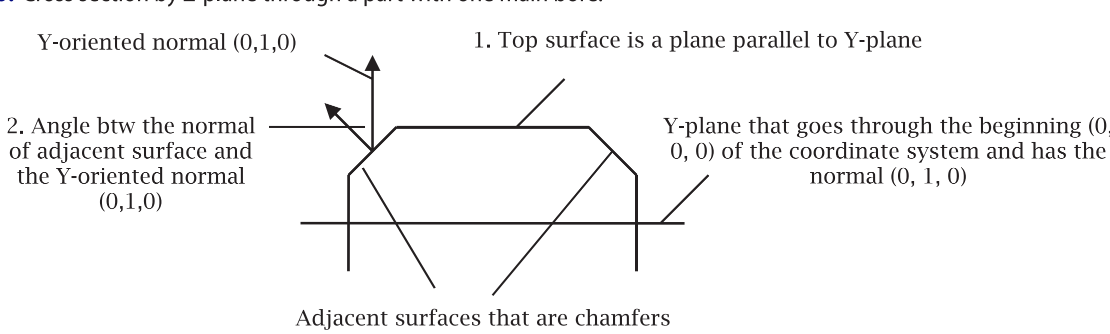

Figure 11. Cross section by Z-plane through a part that has chamfers.

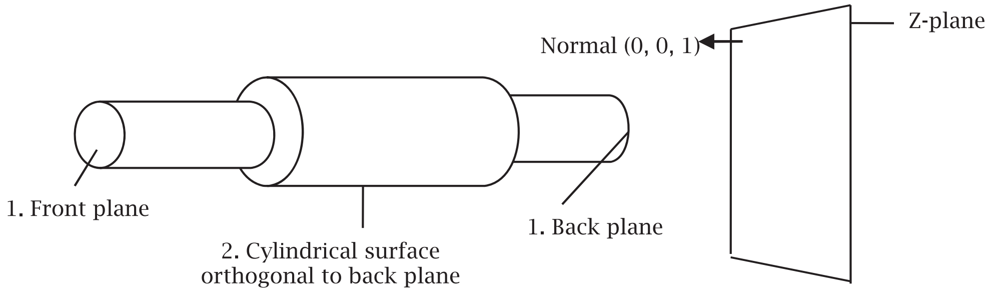

Figure 12. Rotational part stepped to both ends with no shape elements.