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Methods for automated manufacturability analysis of injection-molded and die-cast parts

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Abstract In this article, a mathematical framework to automatically evaluate the manufacturability of injection-molded and die-cast parts is presented. The framework includes an implemented mathematical algorithm to solve key outstanding challenges in feature recognition for manufacturability analysis of injection-molded and die-cast parts. A novel feature recognition method is developed that is based on decomposing the part into elemental cubes and then, making use of their individual manufacturability, the manufacturability of the part as a whole is evaluated. This article discusses a procedure to obtain a 3D binary representation of the solid model and develops feature recognition techniques to extract critical manufacturability information from this 3D binary array. The outstanding challenges addressed by the method presented include the finding of parting surfaces, parting lines, undercuts, holes, bosses, and finding the direction of mold closure in the context of injection-molded or die-cast parts. The algorithm is implemented using a combination of C++ code and Unigraphics solid modeling software. A short example is presented.

Keywords Design for manufacturing · Feature recognition · Automated manufacturability analysis · Injection-molding · Die-casting

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1 Introduction

A smooth integration between design and downstream applications is crucial for the success of any product. One approach to join design closer to manufacturing is to develop computer-based tools that automate the manufacturability analysis of parts during the design stage. Automated manufacturability analysis research builds from research in design for manufacturing (DFM), computational geometry, computer-aided design (CAD) and feature recognition. While a majority of the successful automated manufacturability analysis research concentrates on machining processes such as milling, drilling, and other material removal-based manufacturing processes, there is less focus on non-machining processes such as injection-molding, die-casting, forging, and stamping. Extending existing methods (i.e., methods for automated manufacturability analysis for milling, drilling etc.) and/or developing new methods to enable automated manufacturability analysis for these common and important non-machining-based manufacturing processes is a basic contribution to DFM. The main contribution of the work presented here is a method that automates the process of evaluating the manufacturability of injection-molded and die-cast parts.

The next section presents a brief background on DFM. Following this, a discussion on DFM with emphasis on molding-type processes is presented along with DFM guidelines for injection-molded and die-cast parts in the form of a structured algorithm amenable to a computer. The limitations of the existing geometric modeling techniques toward automating the DFM analysis for casting type processes and a literature review in the area of feature recognition are presented next. This section discusses existing feature recognition techniques for machining as well non-machining processes. The next section achieves two goals.

First, it leads to the exploration of whether existing feature recognition methods can be directly extended to the problem on hand. Second it brings out feature recognition problems that are specifically associated with the non-machining processes of injection-molding and die-casting. The next section discusses the need for a new feature recognition technique that can solve the problem of automated manufacturability analysis for injection-molded and die-cast parts. Following that, there is a discussion of the central contribution of this article, the manufacturability evaluation algorithm (MEA). How the MEA evaluates the manufacturability of parts is discussed next. At this point, examples to demonstrate how the MEA determines the parting surface, the parting lines, and the undercuts on the part are provided. Also, examples are presented to demonstrate recognition of bosses and holes in a part. Following that, a discussion on determination of direction of mold closure is presented. Finally, there is discussion of implementation, future work, and conclusions.

2 Design for manufacturing

"Economic manufacturing does not just happen. It starts with design and considers the practical limits of machine tools, processes, tolerances, and finishes." This quote from Trucks (1987) articulates the role that DFM has to play in the design of any part. Manufacturability of a part can be specified either qualitatively or it can be quantified. A preferred manufacturability assessment is the one that quantifies the manufacturability in terms of the time and cost of the manufacturing processes involved. The research in this article is based on a manufacturability assessment that includes cost estimates for the part being designed.

Design for manufacturing methods may be applied to four stages of the design process (Mill et al. 1994): the configuration or the conceptual stage, the assembly stage, selection of materials and processes, and the detailed or parametric design stage. The work presented in this article is for implementation mainly during the configuration stages of design. Van Vliet et al. (1999) have reported state-of-the-art techniques in DFM. A comprehensive survey of various manufacturability evaluation approaches can be found in the work of Gupta et al. (1997).

Design for manufacturing is a broad term with many areas of emphasis. Two important areas are DFM for machining processes and DFM for non-machining processes such as injection-molding, die-casting, and stamping. DFM in the context of machining is dealt with in several different manners (Gupta et al. 1994; Priest and Sanchez 1991). Feature-based manufacturing (Shah et al. 1994) uses features to bridge the gap between design and other downstream applications. Features are "chunks of knowledge" that represent the engineering meaning or significance of the geometry of a part (Shah and Mäntylä 1995).

Using a feature-based approach, the evaluation of part manufacturability at the configuration and parametric design stages has been dealt with in the monograph by Dixon and Poli (1995). Poli et al. (1988, 1990) and Dastidar (1991) discuss how the presence and location of holes, projections, and other features affect the tooling and processing cost for injection-molding, die-casting, and stamping (Poli 2001). The next section discusses the algorithm of Dixon and Poli (1995).

3 DFM for injection-molding and die-casting

One of the initial and critical needs for developing design for manufacturability assessment is to develop knowledge of what can and cannot be manufactured. The initial representation for this manufacturing capability is generally stored in the manufacturing engineer's experience. Traditionally, through collaboration with design and manufacturing engineers, the possibility and cost of producing some part is determined.

Our approach to developing an automated manufacturability evaluation tool builds on the manufacturability knowledge cataloged by Dixon and Poli (1995) (Poli 2001; Poli et al. 1988, 1990). Dixon and Poli (1995) have determined the characteristics of parts that determine part manufacturability and cost. They have reduced the manufacturing engineer's knowledge of injection-molding and die-casting to a set of part features and feature characteristics. We begin our efforts building on this knowledge (Dixon and Poli 1995).

Building on the efforts of Dixon and Poli (1995), two immediate tasks for automated manufacturability analysis of injection-molded and die-cast parts are apparent. The first is to decompose the manufacturability guidelines from Dixon and Poli (1995) into a structured algorithm that can be coded for automation. This coded algorithm will require information like the holes, bosses, parting lines, and other part features (Dixon and Poli 1995) from the solid model (Mortenson 1985; Zeid 1991) of the part. The solid model of the part does not explicitly store such information. The second task then, is to develop methods that will enable a computer to extract the required information and feed it as input to the structured algorithm. The outcome of this effort will be a computer-implemented algorithm that takes the solid model of an injection-molded or die-cast part and reports its manufacturing cost. Development of such a manufacturability evaluation tool that automates the DFM guidelines of Dixon and Poli (1995) is the major contribution of the research presented in this paper.

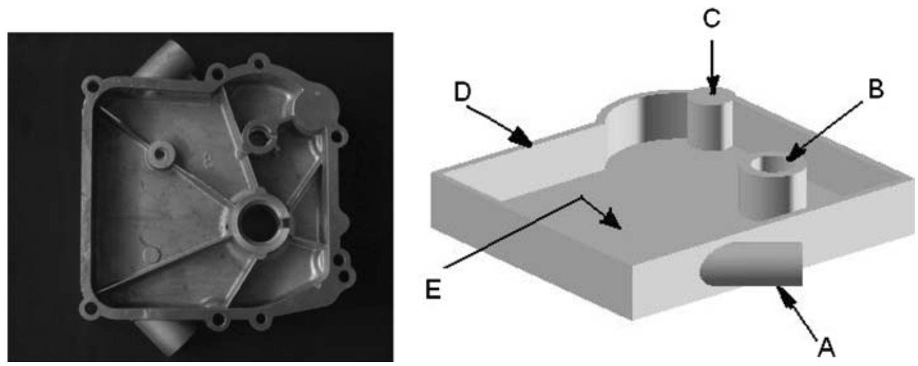


Fig. 1 A crankcase cover and its solid model representation showing some features critical to die-casting

4 Development of a structured DFM algorithm

During the configuration or conceptual stages of design, certain features present on the part drive its manufacturing cost. With this underlying premise, Dixon and Poli (1995) have devised a way of quantifying part manufacturability. The "how difficult" question pertaining to the part manufacturability is essentially answered by viewing the part in terms of its features. The features present on the part are then correlated with the manufacturing cost data tabulated with the help of injection-molding and die-casting industries. A more detailed discussion for quantifying manufacturability in the above-mentioned fashion is beyond the scope of this paper and can be found in the work of Dixon and Poli (1995) (Poli 2001; Poli et al. 1988, 1990). Here, an algorithm is developed that extends the manufacturability analysis methods from Dixon and Poli (1995) to allow computer implementation and eventually complete automation. The algorithm is presented through the use of an example.

The left portion Fig. 1 shows a picture of a crankcase cover for a lawn mower engine. The right portion of Fig. 1 shows a simplified solid model of the same. The crankcase cover is a representative of the vast majority of die-cast parts used in the automobile and aircraft industry. Because the processes of injection-molding and die-casting are so similar, the influence of part geometry on manufacturability is almost the same for both these processes (Dixon and Poli 1995). So, although the part shown in Fig. 1 is representative of the die-casting process, the discussion applies equally well to injection-molded parts.

For the crankcase cover shown in Fig. 1, features labeled A, B, C, D, and E affect the processing and tooling cost during the die-casting process. Using common terminology, these features are (A) an external undercut, (B) a hollow boss, (C) a cylindrical boss, (D) a wall feature, and (E) a depression formed by the walls. Note that feature A is an external undercut because the protruding boss has a concentric hole that cannot be manufactured by the primary motion of the core. The ribs supporting the hollow boss of the crankcase and several other features of the part have been intentionally omitted in the solid model for simplification of discussion. In what follows, the use of the manufacturability guidelines from Dixon and Poli (1995) will be demonstrated for the specific case of the crank case cover in Fig. 1.

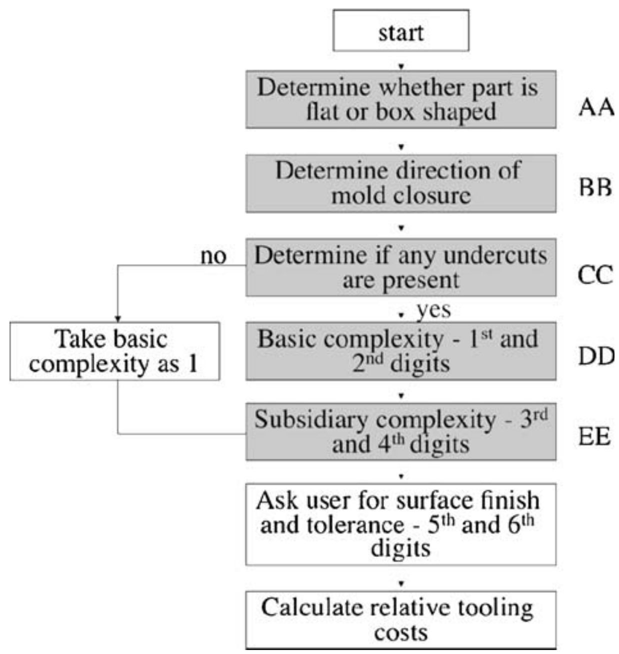


Fig. 2 A flow chart showing the primary steps of the global manufacturability analysis algorithm

As a first step, the manufacturability guidelines from Dixon and Poli (1995) are decomposed to produce a manufacturability analysis algorithm. Structuring the guidelines in such a manner not only facilitates automation, but also clarifies the specific feature recognition needs of injection-molding and die-casting. Shown in Fig. 2 is the global algorithm for determining manufacturability. Each step of the global algorithm will be further subdivided into a separate feature recognition algorithm. In this global algorithm, a shaded box means that to answer the question, feature recognition is needed.

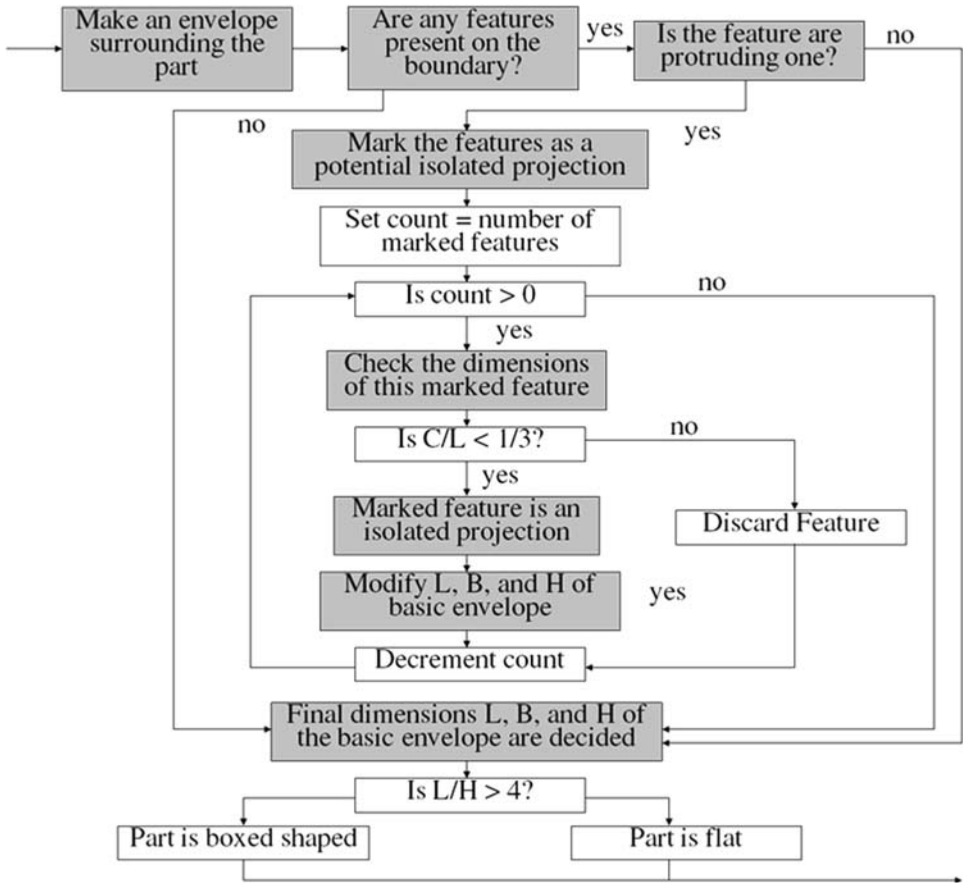


Fig. 3 A detailed algorithm to determine whether a part is *flat or box shaped*. Step AA for the global manufacturability analysis algorithm

For example, at step AA, a determination of whether the part is flat or box-shaped needs to be made because flat-shaped parts are cheaper to manufacture (Dixon and Poli 1995). Figure 3 shows the expanded algorithm required at step AA. Moving through the algorithm in Fig. 3, questions concerning the presence and characteristics of features need to be answered. In the context of the part shown in Fig. 1, the feature labeled A is a boundary feature and it should be recognized and given as an input to the algorithm in Fig. 3.

Similar expanded algorithms for each of the steps, BB, CC, DD, and EE in the global algorithm of Fig. 2 have been developed. These expanded algorithms are found in the Appendix. In the next few paragraphs, a brief explanation of some important features that drive the part manufacturing cost is presented.

Continuing through the example, finding the direction of mold closure (step BB of Fig. 2) is the most crucial feature recognition task. Usually, the direction of the main recess or hole becomes the direction of mold closure. For the crankcase cover, the direction of mold closure is along the direction of the largest depression i.e., along feature E. From the perspective of an automated DFM analysis, a computer should recognize the presence of the hole feature E, then recognize that it is also the largest hole feature and finally decide that the direction of mold closure would be along feature E.

Another important factor that drives the cost of injection-molded and die-cast parts is the number of undercuts present in the part. The feature labeled A in Fig. 1 is an external undercut. A computer needs to recognize this fact. While calculating the basic complexity for step DD in the global algorithm, the algorithm should not only know the number and location of undercuts, but also should identify the mold parting surface and the parting line. Additionally, knowledge of whether the parting surface is planar or non-planar is also required. The term basic complexity in step DD of Fig. 2 accounts for the number of undercuts a part contains. A greater number of undercuts in a part results in a greater part complexity. Also a non-planar parting surface means a higher manufacturing cost when compared to a planar parting surface.

The subsidiary complexity, which is calculated in step EE of the global algorithm, is used to quantify the die-cavity detail required to manufacture the part (Dixon and Poli 1995). To determine the subsidiary complexity, the presence and characteristics of holes, bosses, ribs, and walls needs to be determined. Once answers to all the questions in steps AA through EE is determined, the manufacturability of the part can be determined in terms of its relative manufacturing cost as compared to a standard washer (Dixon and Poli 1995).

5 Related work in feature recognition

Geometric modeling (Mortenson 1985) and CAD (Zeid 1991) play a crucial role in part design. However, the solid model of a part suffers from some deficiencies with respect to DFM. CAD data is stored as a boundary representation (B-rep) model. Such models contain low-level data like points, edges, curves, and faces. Entities needed for manufacturability assessment such as bosses, holes, distance between holes, and wall thickness are not explicitly available in B-rep models. The need for extraction of such information from the computer-based mathematical representations of the part leads us into the area of feature modeling. Feature modeling is used to capture the design intent of features (Shah and Mäntylä 1995) with the intention of providing improvements to ordinary geometric modeling techniques. Identifying features from the solid model of a part then becomes a vital step in automated manufacturability analysis. This step is commonly referred to in the literature as feature recognition. In this article, the term "feature recognition" is somewhat loosely used and is intended to encompass all "information-extracting" procedures that are needed for an automated DFM analysis of injection-molded and die-cast parts.

Recognizing part features from a solid model has been the area of active research for at least the past 18 years. Still, a comprehensive technique for feature recognition is missing. The literature on feature recognition focuses mainly on applications related to manufacturing processes in the machining domain. Research into feature recognition for non-machining processes has received less effort. A prominent characteristic of the research presented in this article is that it investigates the applicability of both existing and new feature recognition techniques to the manufacturability evaluation of non-machining processes like injection-molding and die-casting. In the next few paragraphs, we first review the literature in feature recognition for machining processes and later discuss feature recognition efforts for non-machining processes of injection-molding and die-casting.

Many feature recognition techniques focus on process planning, tool path generation, and NC part programming. Henderson et al. (1994) have surveyed the various feature identification techniques used to extract features from B-reps of parts. The rule-based approaches (Henderson 1984; Kyprianou 1980; Vandenbrande 1990) use artificial intelligence techniques to develop a set of feature rules. The drawback of this approach is that rules tend to be specific to a set of features. In addition, rule-based algorithms tend to be slow because of the enormous amount of geometric data that they must scan through.

Another successful feature recognition technique is the graph-based approach (Joshi and Chang 1988; Sakurai and Gossard 1988). This approach consists of representing the topological information of the B-rep model of a part using graph theory. This graph representation of the solid model is divided into sub-graphs. If any sub-graph matches with a feature graph, a feature is found. The drawback of this approach is that interacting features tend to confuse the algorithms of this approach.

Many other approaches to feature recognition have been tried with different ranges of applicability and degrees of success. Neural networks have been applied to the problem of feature recognition in the work of Prabhakar (1990). Woo (1982) developed the alternating sum of volumes (ASV) approach in his pioneering work in the field of feature recognition. The non-convergence of Woo's algorithm for certain geometries was investigated by Kim (1994), who then presented a refined algorithm. Kramer et al. (1993) created a library of material removal shape element volumes (MRSEVs). Regli et al. (1994) solved the problem of taking a CAD model and extracting machinable features that contain the complete set of alternative interpretations of the part as collection of MRSEVs (Regli 1995; Regli and Nau 1993). The delta volume is thus decomposed into MRSEVs and this database is used to evaluate the manufacturability in the context of machining.

Vandenbrande (1990) gave a powerful method of feature recognition in which rules and procedures manipulate the data and generate hints for the presence of machining features. Promising hints are further processed to complete the feature volumes and later checked for their machinability. Requicha and Han (1998) describe an Integrated Incremental Feature Finder that works in a four-step approach: hint, generate, test, and, repair. This approach is able to recognize three types of features: holes, slots, and pockets. Gadh (1994) discusses an innovative method for creating the design using preset features with the aim of later utilizing them to perform manufacturability analysis. Lei and Qamhiyah (2000) present a novel procedure for the extraction of form features from the CAD model of a part. In their approach, the solid model is digitized and features are extracted using wavelet transforms.

Relative to machining processes, casting type processes have received less attention in the feature recognition literature. Some literature, which is relevant to the problem presented in this article, is presented next. Chen et al. (1993) obtained the potential undercut surfaces from the B-rep of the part by using the convex-hull decomposition methods. Further, using visibility maps, they found the optimal mold closure direction such that the number of undercuts (i.e., partially or totally invisible surfaces) are minimized. The optimal direction found is one of the infinite numbers of possible directions and is hard to obtain. This work does not address internal undercuts. Nee et al. (1997) gave a classification for the types of undercuts. Further they presented rules that manipulate B-rep model data and decide whether a surface is an undercut by firing rays from the surface center and studying its behavior. This work did not address undercuts on free form surfaces. As a continuation of this work, Nee et al. (1998) also presented a method for finding the optimal mold closure direction and the 3D parting lines. A key feature of their algorithm is that it also considers the volume of the undercut when finding the optimal molding direction. Fu et al. (1999) gave the definitions and classification for the undercuts. They also presented important undercut parameters and feature recognition techniques to find them. Ye et al. (2001) gave a method that combines the graph-based and hint-based approaches of feature recognition and recognizes undercut features.

The problem of finding parting lines was also addressed by Ravi and Srinivasan (1990) by proposing nine factors that should be considered when constructing 3D parting lines. Tan et al. (1990) used the dot product of the surface normal and the direction of mold closure as a criterion to define tentative parting lines. An approach to find parting lines by slicing a solid model was proposed by Wong et al. (1998). Weinstein and Manoocheri (1997) treated the mold closure direction and the parting line location as design variables and proposed minimizing the manufacturing cost by treating it as a function to be optimized.

From a review of current and past efforts, the following conclusions can be drawn.

- Automated manufacturability analysis is done primarily in the context of machining processes such as milling, drilling, and other material removal processes. Non-material removal processes such as injection-molding or die-casting have received less attention.
- Feature recognition is done primarily with the aim of carrying out Computer aided Process Planning and NC tool path generation.
- All the feature recognition efforts in the molding/casting domain are based on a common premise of using visibility maps and "feature rules" that manipulate B-rep solid model data to obtain undercuts.
- The direction of mold closure is found by searching through a spherical domain for a direction along which the number of undercuts is minimum.

A key focus of this work is to present new and/or alternative methods that will enable feature recognition and automated DFM analysis to be applied to molding type processes.

6 Feature recognition for injection-molding and die-casting

One of the most important results of developing a structured algorithm in the earlier section is that the critical feature recognition needs for injection-molding and die-casting are identified. Also, key characteristics of recognized features that need to be known are identified. Both recognition of features and determining key characteristics of these features will be referred to as "feature recognition problems" from here forward.

Solving feature recognition problems with existing feature recognition techniques and developing new feature recognition techniques as needed for determining the manufacturability of injection-molded and die-cast parts is the main aim of this research. Before developing new methods, the applicability of existing feature recognition techniques is investigated. The solution to each required feature recognition problem is explored with existing feature recognition techniques such as rule-based techniques, graph-based techniques, and ASVs. If it is possible to fully or partially solve a particular feature recognition problem, then "ok" is marked in the matrix partially shown in Fig. 4. On similar lines, feature recognition problems that could not be solved by a particular technique are marked "X". By evaluating the applicability of existing feature recognition methods to the needs of feature recognition for injection-molding and die-casting, the outstanding research problems are identified.

It should be noted that an "ok" for a particular combination of a feature recognition problem and a feature recognition technique does not imply that the technique will identify the feature under all circumstances. For example, the graph-based technique (Joshi and Chang 1988; Sakurai and Gossard 1988) does recognize holes, but will not recognize holes if a set of intersecting holes are present. Because of the complexity of solving feature recognition problems, the use of each of these feature recognition methods is currently limited to simplified features with no tolerance for arbitrary interactions between features. Extending these methods to more general problems involving feature interaction remains a research problem beyond the scope of this article.

Figure 4 reveals that there is no single existing method that currently addresses all the problems in automated DFM analysis of injection-molded and die-cast parts. Though other methods could be extended to address additional features, thus turning one of the "Xs" in Fig. 4 to an "ok" such research is beyond the scope of this article.

In general, the use of existing feature recognition algorithms is limited to simple planar parts, or parts with limited numbers of curved features. A shortcoming of rule-based approaches, such as those proposed by Henderson (1984), is that they become very inefficient when handling

Fig. 4 Summary of the applicability of existing feature recognition techniques as applied to the feature recognition needs of injection-molding and die-casting shown in part

Problem \ Method	Rule Based [9,15]	Graph Based [12,31]	Alternating Sum of Volumes [41]	Regli et al. [27]	Chen et al. [1]	Nee et al. [19,20]
Basic Envelope	X	X	ok	X	X	X
Boundary Features	ok	ok	ok	ok	X	X
Recess	ok	ok	ok	ok	X	X
Undercuts	X	ok	ok	X	ok	ok
Direction of Mold Closure	X	X	X	X	ok	ok
Parting Surface and Parting Line	X	ok	X	X	ok	ok
Peripheral Height	X	X	X	X	X	X
Hole	ok	ok	ok	ok	X	X
Boss	ok	ok	ok	ok	X	X
Ribs and Walls	ok	ok	X	ok	X	X

a large amount of geometric data. The approaches of Regli (1995) and Woo (1982) cannot be used directly for feature recognition of an injection-molding manufacturability assessment. For example, algorithms given by Regli decompose the delta volumes into MRSEVs (Kramer et al. 1993) and develop the best machining plan for a particular feature. This ability does not have direct applicability to injection-molding or die-casting. Due to the basic differences in machining and molding or casting, the approach of extending machining-based feature recognition methods such as Regli's (1995) to molding and casting is unclear. For casting and molding, it is important to recognize a boss feature. Recognizing the presence of a boss is more important for the problem of injection-molding and die-casting than generating a machine tool path that traverses the delta volume corresponding to that boss.

Furthermore, some feature recognition problems that are specific to the injection-molding and die-casting process have received less focus in the literature. The problems of finding a parting surface and finding the direction of mold closure are specific to the die-casting process. Determining the parting surface is crucial to determining manufacturability for a part to be molded or cast.

Below, a MEA is proposed that directly addresses the issues specific to molding and casting. Compared to the literary works of Chen et al. (1993) and Nee et al. (1997, 1998), the MEA demonstrates an alternative approach towards solving feature recognition problems for molding type processes. This article shows how the MEA finds the direction of mold closure for the part and also addresses the problem of finding the parting surface and 3D parting lines of the part.

7 A manufacturability evaluation algorithm for injection-molding and die-casting

In this section, a method is developed to perform feature recognition that will enable automated manufacturability evaluation for injection-molding and die-casting. The method is extended to a quantified algorithm and the associated computer code is used to explore a simple example. The underlying philosophy and approach of this algorithm builds upon both the characterization of injection-molded and die-cast parts as found in Dixon and Poli (1995) and the fundamental physical nature of molding and casting processes. The fundamental physical notion used to inspire this algorithm is that each surface of the part must come into contact with the mold. Thus, the interaction of solids and voids (from the part's perspective) leads to a basic understanding of what can and cannot be molded or cast. Motivation for building upon the work of Dixon and Poli (1995) is based on the wealth of manufacturability knowledge already partially codified by their efforts.

The first step of the method is to represent the solid model of the part in terms of a 3D binary array of 1 s and 0 s. The basic aim of this algorithm is to rebuild the solid model of a part in terms of solid cubes represented by 1 s and void cubes represented by 0 s. Such a representation is also known in the solid modeling literature as the exhaustive enumeration type of decomposition model. Representing the solid model of the part in such a "voxelized" form has key advantages for determining molding manufacturability. These advantages are elaborated below.

7.1 Part representation: solid cubes and void cubes

In injection-molding and die-casting, a surface of a part is produced by allowing the polymer or molten metal to cool against the walls of the mold. For example, consider a cube shaped part as shown in Fig. 5. This cube has six faces, and if this cube is to be produced by die-casting, its surfaces will be formed by the surfaces of the mold. For example, surface A will be produced because a corresponding surface is present in the mold. Surface A of the cube can and will be produced only if the corresponding surface of the mold can reach the surface A.

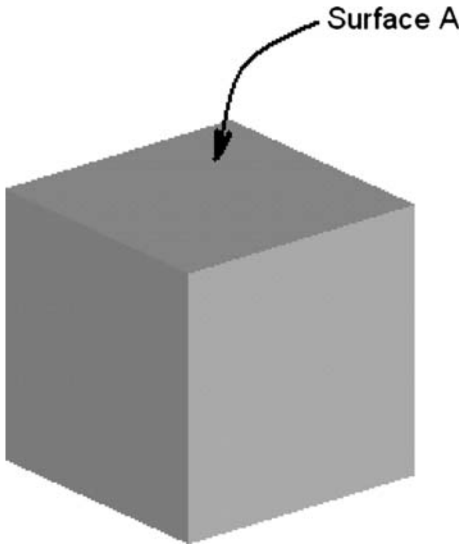


Fig. 5 A simple part to be molded

In general, the part geometry in Fig. 5 is manufacturable either by molding or casting because the six surfaces of the mold can come into contact with all six faces of this part. Simply put, if the surface of the mold can move toward the part starting from infinity and ending on the part, at no point will the mold path experience an obstacle of any kind. A necessary condition for a part to be manufactured is that there is no obstacle, or a solid cube, between the surface A that is to be produced and the mold surface that will produce it. If another solid cube (physically, an obstacle) is present between the two, then surface A of the part is not manufacturable. Thus, decomposing a part into a 3D array of solid and void cubes allows us to use the relationship between solid and void cubes to determine the part manufacturability.

Consider the cubic part shown in Fig. 6. The part is decomposed into 27 building blocks. The solid cube building blocks (1 s) are classified into two categories.

1. Interior cubes: the building block solid cubes that lie completely inside the part. These are surrounded on all six sides by other solid cubes.
2. Boundary cubes: the building block solid cubes that are surrounded by other solid cubes on less than six sides and exposed on the remaining sides.

Interior solid cubes signify a location in the part where the molten liquid metal or the polymer flows and they do not directly affect the manufacturability. In terms of the decomposed part, only boundary cubes "get manufactured." Boundary cubes come in contact with the surface of the mold. They form the boundary of the part and thus are critical to determining part manufacturability.

During the configuration stages of design, the cost and subsequently the manufacturability is driven by accessibility

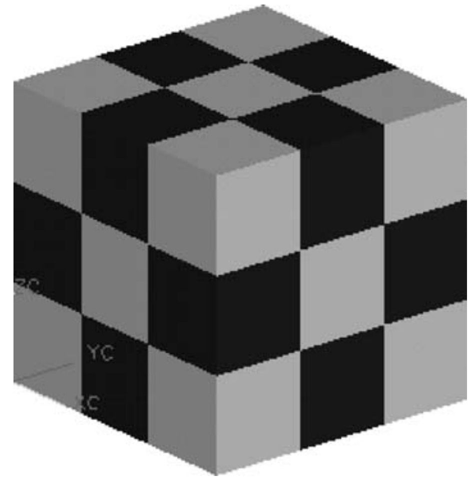


Fig. 6 A candidate part decomposed into small building blocks

of all the part surfaces. During the parametric stages of design (i.e., when deciding the dimensions), manufacturability is driven by accessibility as well as thickness of walls etc. Limiting the scope to configuration design, we can conclude that interior solid cubes do not affect manufacturability. They would certainly play a significant role in DFM analysis during parametric stages of design. For example, parts with non-uniform wall thickness are difficult to manufacture and counting the number of interior cubes would become a possible method for quantifying the thicknesses of two different features. For the work presented in this article, one can certainly assert that boundary cubes are crucial to finding part manufacturability.

To demonstrate the use of interior and boundary cubes, consider as an example, the block with a cylindrical boss as shown in Fig. 7. The cylindrical boss has a central hole. The MEA represents the inner surface of the hole by boundary solid cubes. Using the direction of mold closure as given in Fig. 7, the boundary cubes that form the inner surface of the hole cannot be manufactured; thus the hole is a non-manufacturable feature. The hole in Fig. 7 could be manufactured by a side-action mold closing. Such side-action mold closure increases the cost of manufacturing the part and the hole that needs to be side-manufactured gets classified as an undercut. Though the methods presented here extend directly to determining side action molded features, doing so remains future work.

Based on a binary representation, the basic aim of the MEA is to represent the solid model of a part in terms of interior cubes and boundary cubes and to evaluate the manufacturability (or accessibility) of every boundary solid cube.

If every boundary solid cube found in the model is manufacturable, the part is manufacturable by die-casting and injection-molding. If boundary cubes are not

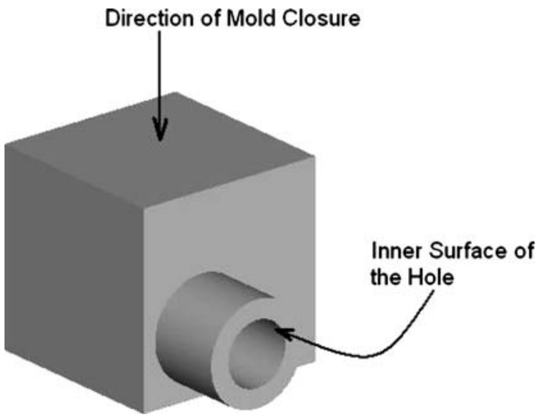


Fig. 7 A simple part with a hollow boss

accessible for the given direction of mold closure, the part as a whole cannot be injection-molded or die-cast. By representing the solid model of a part in terms of solid cubes and void cubes, the evaluation of manufacturability of the whole part is reduced to considering the manufacturability of individual cubes. In addition to determining the manufacturability of the part, individual cubes will also be used below to determine the direction of mold closure, the parting surface and the presence of hole and boss features. It is pointed out that the key characteristic of the MEA is that it uses a 3D binary representation, and performs feature recognition without processing geometric data in the form of points, edges, and faces. A brief discussion on obtaining the binary representation is given next, which is followed by a brief discussion on methods for classifying the solid cubes into interior and boundary cubes.

7.2 Obtaining the binary representation

One of the strengths of the feature recognition technique developed in this article is the simplicity of obtaining a binary representation of the solid model. Here the aim is to decompose and rebuild the part in terms of cubes of height *h*. It should be noted that many commercially available CAD software have the ability to voxelize a given solid model. A comparative study of the voxelization method presented here and that used in commercial software is beyond the scope of this article.

The size of the cubes that become the building blocks affects the ability of the MEA to identify features. A smaller size elemental cube allows a smaller feature to be identified. However, a smaller size cube requires increased computational time and cost. The largest viable value for *h* is dictated by the size of the smallest feature that the MEA needs to recognize. In this article, a cube size of $1\ \text{mm} \times 1\ \text{mm} \times 1\ \text{mm}$ was taken for test parts of approximate size $70\ \text{mm} \times 40\ \text{mm} \times 20\ \text{mm}$.

With *h* determined, the solid model of the part is sliced. Three orthogonal slices are made through the solid to reduce the solid to a three-dimensional mesh. The implementation of the meshing is shown in Figs. 8, 9. Solid and void cubes (1 s and 0 s) are obtained by Boolean algebra, i.e., a straight-forward intersection of a solid cube (equal to the mesh size) with the part solid model at every location. If the intersection operation is successful, then a 1 is marked at that location, if the intersection fails then a 0 is recorded for that location. If a cube is more than 50% solid, it is considered solid and marked a 1, otherwise it is marked a 0. This procedure is used to obtain a binary representation for the entire part. It should be noted that the mesh formed by the 1 s and 0 s comprises of equal-sized cubical blocks. In this aspect, the mesh is different from an octtree representation (Jackins and Tanimoto 1980) where the mesh is coarse in some regions of the part while it is fine in some other portions of the part. Additionally, an octtree representation has black nodes (corresponding to material), white nodes (corresponding to empty space), and gray nodes. Every gray node is further sub-divided into

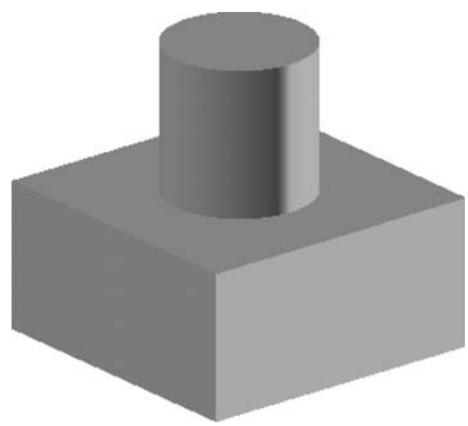


Fig. 8 A block with a cylindrical boss

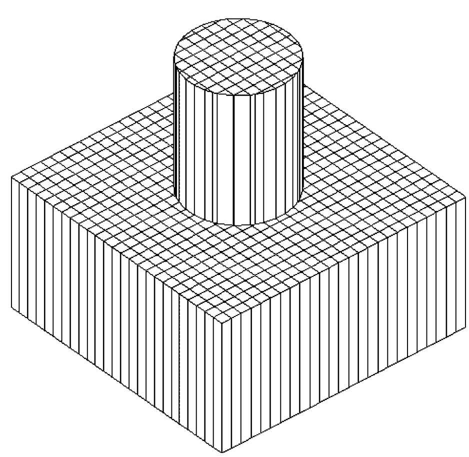


Fig. 9 The sliced version of the part

eight octants and each sub-node (corresponding to every octant) is further classified as black, white, or gray. This process is continued till a desired level of resolution is achieved. The binary representation used in MEA does not use such a space sub-division algorithm, but classifies the solid only in terms of material or empty space. An octtree representation would likely increase the implementation speed of the MEA and reduce the computer memory storage requirements. A comparative study regarding the performance of the MEA (i.e., its speed, the accuracy of features recognized etc.) while using an octtree data representation as against the uniform mesh that is currently being used is beyond the scope of this paper and remains as future work.

7.3 Type classification of solid cubes

The binary data developed above will be used for solving feature recognition problems. Before using this data to find the parting surface or recognize holes and bosses, the solid cubes are classified as interior or boundary cubes. The classification is done by gathering the neighborhood information for all the solid and void cubes. For example, the binary representation for a rectangular slice with a rectangular hole is shown in Fig. 10.

Figure 10 shows solid cubes on the boundary of the inner rectangle being classified as boundary cubes. Solid cubes at the boundary of the part are also classified as boundary cubes. In the end, every cube will have the following three pieces of information: Category (1 or 0), Location (x, y, z), and Surrounding Information (1 1 1 1 1 1). The surrounding information records the presence of solid cubes next to the six faces of the cube under consideration. For example six 1 s mean that the cube is totally surrounded by solid material, thus the cube gets classified as an interior cube.

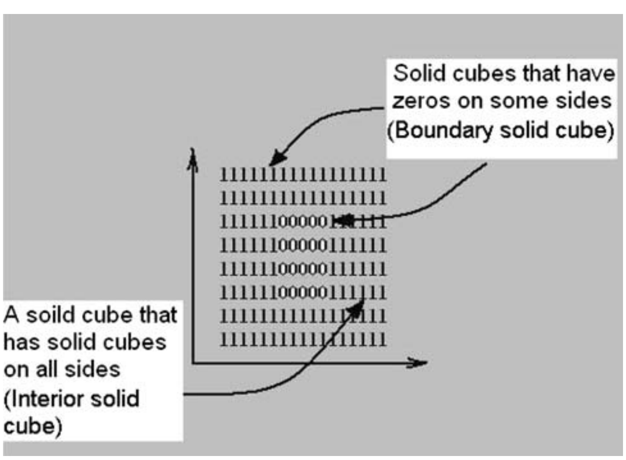


Fig. 10 Classifying solid cubes as Type I or Type II

8 Manufacturability of the part

The binary data obtained above is now used to answer the yes or no question on manufacturability of the part, obtaining the parting surface of the part, determining the undercuts (Dixon and Poli 1995), recognizing bosses and holes present in the part, and determining the direction of mold closure.

8.1 Determining part manufacturability

The MEA investigates all the void cubes for accessibility. The void cubes signify places where the mold needs to be present. Mold walls and cores are represented by void cubes. If a void cube is surrounded on all six sides by solid cubes, it means that the void cube cannot be accessed. In such cases the void cube, and hence the part, cannot be manufactured by a die-casting or injection-molding process. The MEA scans through the 3D binary array and checks whether every void cube is accessible from at least some direction. Based on the results of this scanning, the MEA then reports the manufacturability of the part as a yes or a no.

8.2 Undercuts

Figure 7 shows a hole feature that needs to be side-manufactured because it would otherwise obstruct the mold closure. Features of this type are defined as undercuts. In short, undercuts are features that are inaccessible during the primary mold closing motion and need extra motions of the mold. In terms of interior and boundary solid cubes, undercuts are surfaces formed by boundary solid cubes that cannot be accessed and thus manufactured for a given direction of mold closure. The distinction between a totally non-manufacturable void cube and a solid cube that forms an undercut depends on the surrounding cubes. A totally non-manufacturable void cube is surrounded on all six sides by solid cubes. The solid cube forming an undercut is always accessible from at least one of the six directions. However, the motion of the core, along such a direction, is inconsistent with the direction of mold closure. The result is a required extra motion of the core and an increased cost of tooling.

The MEA investigates all boundary solid cubes for accessibility. For a particular surface to be manufacturable, the boundary solid cubes that form this surface must be accessible by the walls of the mold. For example, Fig. 11 shows boundary solid cubes that cannot be accessed if the direction of mold closure is along any one of the four directions shown by the arrows.

For a given direction of mold closure, the MEA finds all boundary solid cubes that cannot be reached by the mold

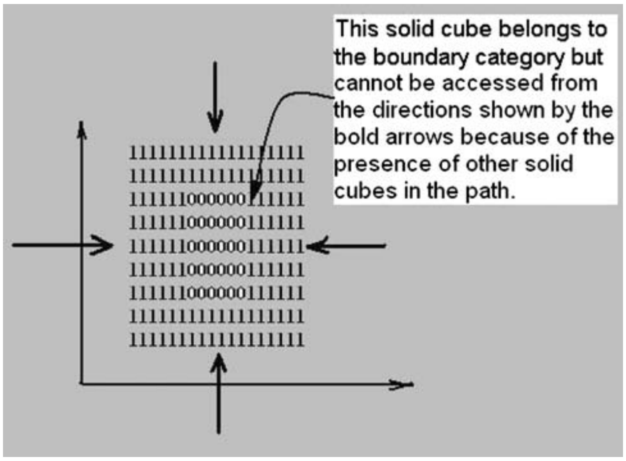


Fig. 11 Illustrating the accessibility analysis to find undercuts

wall. Two adjacent boundary solid cubes that both have inaccessible surfaces are combined or "clubbed" to form what is an inaccessible surface. Thus, inaccessible boundary solid cubes found by the MEA are clubbed together to form a surface or surfaces. The surfaces formed by these solid cubes are the surfaces of the features that form the undercuts. The number of such separate surfaces identified by the MEA is the number of undercuts present in the part. The MEA then reports the number of undercuts present in the part.

Shown in the left portion of Fig. 12 is a rectangular block that has one cylindrical hole and a rectangular hole perpendicular to the direction of mold closure. The right portion of Fig. 12 shows that these two holes are recognized as undercuts by the MEA.

An essential difference between the methods presented here and the ones surveyed earlier in the literature is that the present method uses a voxelized model to do all feature recognition tasks as opposed to the B-rep data used in others. The methods presented in the literature (Chen et al. 1993; Nee et al. 1997, 1998; Ye et al. 2001) on undercuts involve extensive definitions or "feature rules" and are sometimes limited to planar surfaces or simple revolved surfaces. In some instances (Chen et al. 1993), internal undercuts cannot be dealt with. The MEA views undercuts as groups of boundary solid cubes inaccessible to the mold walls. Our method can deal with internal as well as external undercuts that are present on planar or curved free form surfaces.

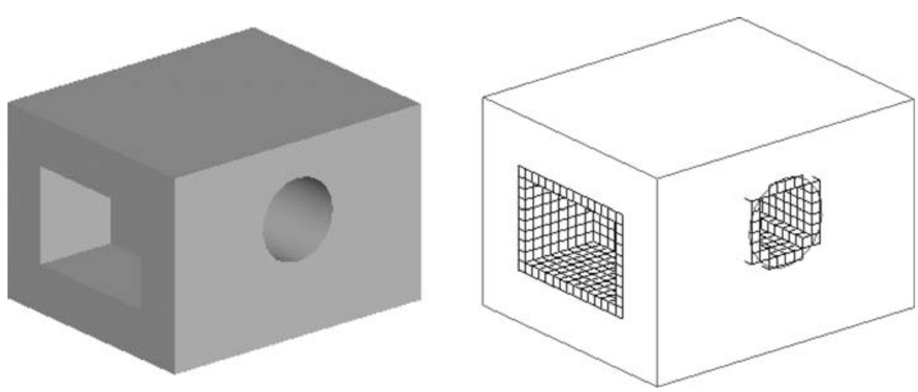
8.3 The parting surface

Determining the mold parting surface is a key step in the manufacturability assessment of molded and cast parts. Using the definition in Dixon and Poli (1995), the parting surface is defined as a surface, in one or more planes, for which the portion of the part on either side of the surface can be extracted from a cavity conforming to the form of the outer shape of the portion in a direction parallel to the direction of mold closure.

Figure 9 shows the sliced form of the solid model, which is a set of rectangular columns parallel to the Z-axis. In the binary language, this column will be a set of 1 s and 0 s arranged in a vertical fashion. Using the binary representation of the solid, the parting surface lies just above the uppermost 1 in every column and just below the lowermost 1 in every column. To find the parting surface, the MEA traverses every column starting from the top. It traverses through all the 0 s (this is the mathematical equivalent of the die-cavity closing-in on the part in the direction of mold closure) until it finds the uppermost 1 in that particular column. The upper parting surface lies just above this uppermost 1. A similar travel from the downward direction leads to the lower parting surface. Figure 13 shows a part and the upper parting surface generated for it by the MEA. The lower parting surface, which is the entire square area, is not seen in Fig. 13. The upper and lower parting surfaces thus found, form a basic step toward finding the 3D parting line of the part.

Furthermore, the "parting line" is defined as a line on the periphery of the part, where the "upper" and "lower" parting surfaces meet each other. Obviously, it is expected

Fig. 12 Illustration of the recognition of undercuts



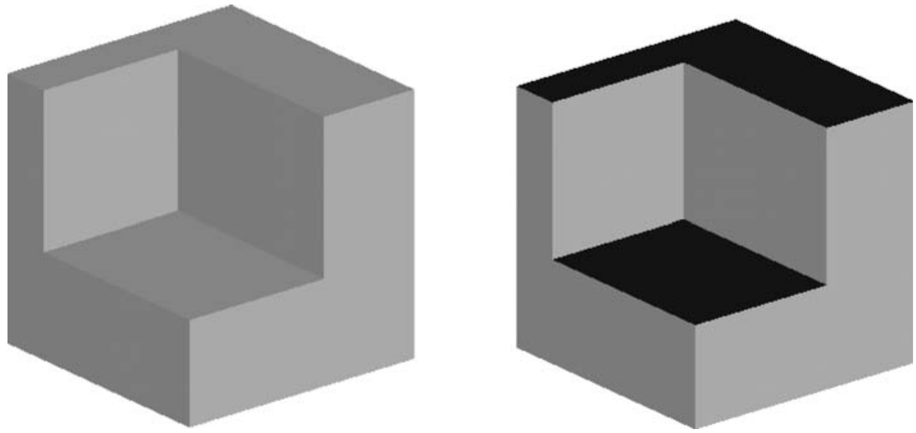


Fig. 13 Determining the parting surface for a simple part

that at certain locations on the periphery of the part, the "upper" and "lower" parting surfaces do not meet each other. In such cases, the "parting line" could lie anywhere between the upper and the lower parting surface. (The MEA starts building the parting surface on the periphery half way between the "upper" and the "lower" parting surfaces). The MEA moves around the periphery of the part and constructs a parting line for the part. The MEA constructs the parting line such that it always lies between the "upper" and the "lower" parting surface and while the parting line is being constructed, the MEA tries to build it in one plane. Finally, if the parting line lies in one plane, the parting surface is considered to be planar. On the other hand, if the upper and lower parting surfaces intersect in different planes, then the MEA is forced to construct parting lines in different planes. If the parting line does not lie in one plane, the parting surface is non-planar. The upper portion of Fig. 14 shows an injection-molded part and the lower left-hand portion shows the parting line that was generated for this part by the MEA. Notice that feature C (shown in the right lower portion of Fig. 14) forces the MEA to construct a non-planar parting line. The parting line generated by the MEA agrees with the parting line present of the actual injection-molded part.

8.4 Recognition of bosses and holes

Recognizing features such as holes and bosses is critical for automated manufacturability analysis. Though solutions for hole and boss recognition developed for machining may be adaptable to the needs of injection-molding we present a new method here. Our method builds upon the binary solid representation. Using this representation, simple rules are used to identify features. Although extracting features from geometric data using a set of rules (Henderson 1984; Vandenbrande 1990) and extracting features from binary data using wavelet transforms (Lei and Qamhiyah 2000) have been dealt with separately, here we combine both methods to extract features. Our approach falls between the rule-based approach (Henderson 1984), Vandenbrande's

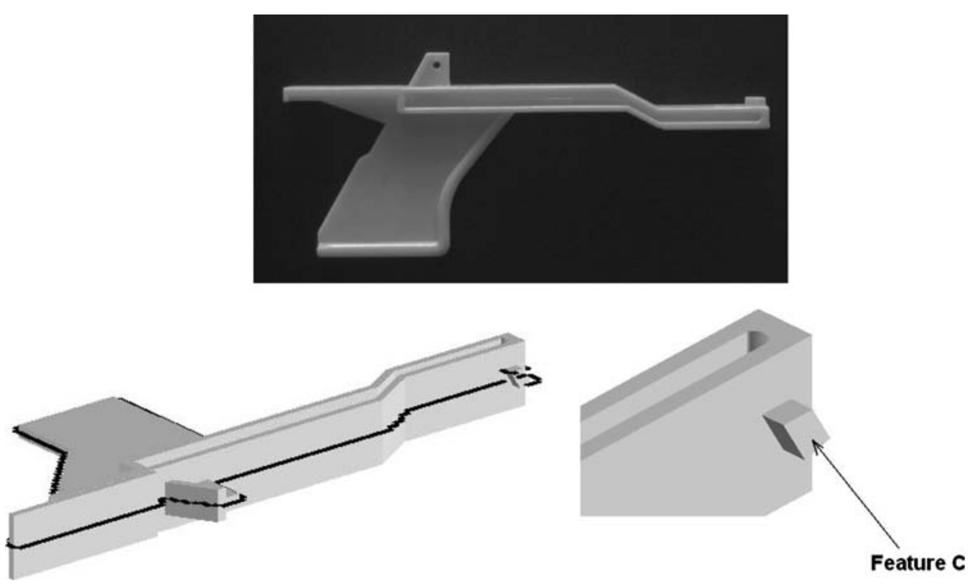


Fig. 14 An injection-molded part and a 3D parting line generated for it by the MEA

approach (Sakurai and Gossard 1988), and the ASVs approach (Woo 1982)]. The hole and boss recognition scheme combines rules and requirements of mold and part contact physics to clump together adjacent solids into potential features. Our approach for recognizing bosses and holes is explained here with the help of the simple part shown in Fig. 15.

The part shown in Fig. 15 is a simple rectangular block that has one cylindrical boss and one cylindrical hole, and A qualitative description of the boss is a solid protrusion coming out of a much wider base. Further, if the shape of this protrusion is circular, it gets classified as a cylindrical boss. In terms of binary data, the boss is viewed as a clubbing of interior solid cubes protruding from a much larger-sized clubbing, and this protruding part is completely enclosed by boundary solid cubes. The MEA recognizes features like holes and bosses using a three step approach of (1) club, (2) connect, and (3) check. This three-step approach is described next.

For the part shown in Fig. 15, consider just the uppermost slice. This uppermost layer, as stored in the binary array, is shown in Fig. 16 where the black-colored dots stand for solid cubes and the gray-colored dots represent void cubes. The black-colored dots completely inside the circular clubbing are interior solid cubes, while those on the boundary are boundary cubes.

The first step of the MEA is to bring together, or club, all the solid cubes in a particular layer. The "clubbing"

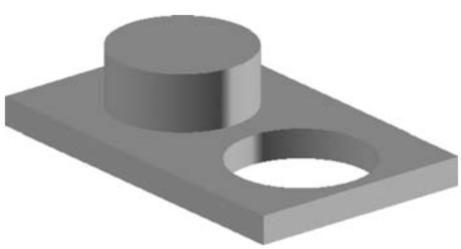


Fig. 15 A simple part with boss and hole

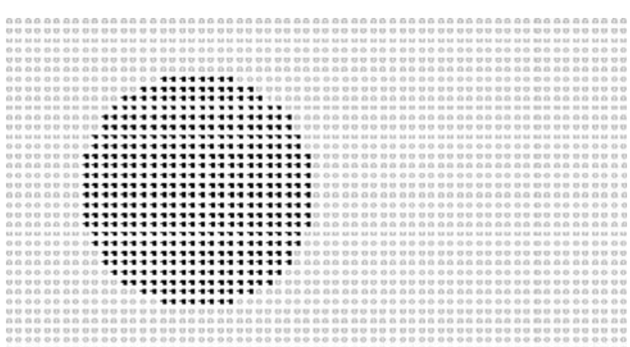


Fig. 16 A binary representation of a layer for the part shown in Fig. 16

formed by this operation is a set of interior solid cubes (belonging to the same layer) connected to one another. The boundary of this set is formed by the adjacent boundary solid cubes. Bringing together solid cubes in such a fashion leads to the extraction of closed boundaries. The presence of boundary solid cubes indicates that the boundary of the clubbing obtained thus far can only be produced if the mold interacts at all those locations. A clubbing of the sort obtained in Fig. 16 indicates that a potential feature is present at that location. The MEA scans through the 3D binary array layer-by-layer, clubbing neighboring solid cubes together, and forms a list of all potential locations for the existence of a possible feature. The procedure described above is the "club" step of the three-step approach. Before describing the second step, the current approach is compared with prior work in the literature.

There are some key similarities and differences between the feature recognition presented here and that of Vandenbrande and Requicha (1993). In their work, the feature recognizer uses certain feature presence rules that correspond to certain topological and geometric relationships to generate hints for the presence of potential features. For example, the presence of a cylindrical or conical surface generates a hint for a hole. Our approach uses the presence of interior solid cubes totally surrounded by boundary solid cubes to generate a hint for the presence of a feature.

After scanning through the binary representation, the "club" step generates hints, or indications, of possible features. Using these hints, the second step of "connect" continues searching for and identifying features. The "connect step" connects "clubbings" found in adjacent layers. For the part shown in Fig. 15, the topmost layer in binary array would look like Fig. 16. Similarly, the layer immediately beneath the topmost one would also look the same. Proceeding in this manner, as the "clubbings" in adjacent layers are connected together, the MEA ends up building a 3D feature by stacking or connecting 2D layers.

As the MEA reaches the bottom of the boss, it attempts to connect or add the base to the feature. However, such an addition is prevented using the following two facts: first, the number of solid cubes forming the first base layer is significantly different from the number of solid cubes present in the last feature layer, and second, the boundary solid cubes in the last feature layer and the first base layer are qualitatively different. More specifically, the boundary solid cubes in the last feature layer and the first base layer have different manufacturing requirements. These two rules that prevent the connection between the last feature layer and the first base layer are briefly described in the next two paragraphs.

As the MEA connects "clubbings" from two adjacent layers, it keeps track of the number of solid cubes in each clubbing. In the case of a cylindrical boss, the MEA will record approximately the same number of solid cubes for "clubbings" from adjacent layers. When the MEA reaches the base layer, the number of solid cubes present in that layer would be different from the number that the MEA has been recording. Since the number of solid cubes present in the base layer is different from the one that the MEA expects it to be, the base is not added or "connected" to the existing stack of "clubbings". The exploration of feature trends while connecting "clubbings" is shown in Fig. 17.

As the feature joins the base, the manufacturing requirements of the boundary cubes change. Specifically, the mold access direction for the boundary solid cubes on the feature and the boundary solid cubes on the base is different. Figure 18 shows location A and location B where boundary solid cubes are located. Location A refers to a boundary solid cube belonging to the boss while Location B shows one belonging to the base layer.

Note that in terms of binary representation, the Location A solid cube has a 0 on its side while the Location B solid cube has a void cube above it. This is shown in Fig. 19. The manufacturing requirement for the Location A solid cube is from its side. The Location B is accessed from its top. As the MEA connects "clubbings" in adjacent layers, its keeps track of the number of boundary solid cubes that have "side-manufacturing requirement" and the ones that have "top manufacturing requirement". For a cylindrical boss, "clubbings" from all layers except the top layer have boundary solid cubes with a side-access manufacturing requirement. The base layer has boundary solid cubes with a top-access manufacturing requirement. This change in manufacturing requirements from the last feature layer to the first base layer, combined with a change in what is expected for feature size, is what the MEA uses to prevent the base layer from getting connected to the existing stack.

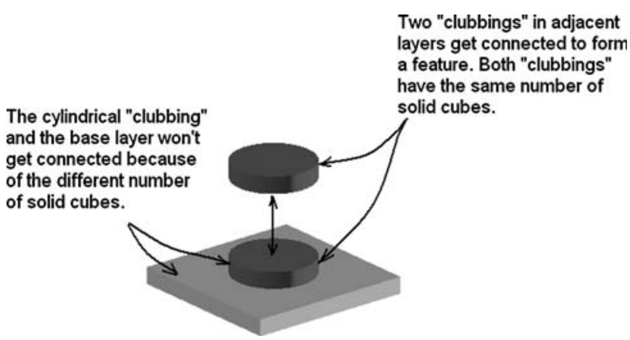


Fig. 17 Illustration of the connection of adjacent layers

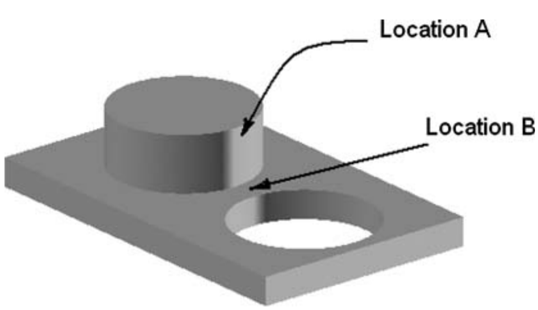


Fig. 18 Illustration of manufacturing requirements

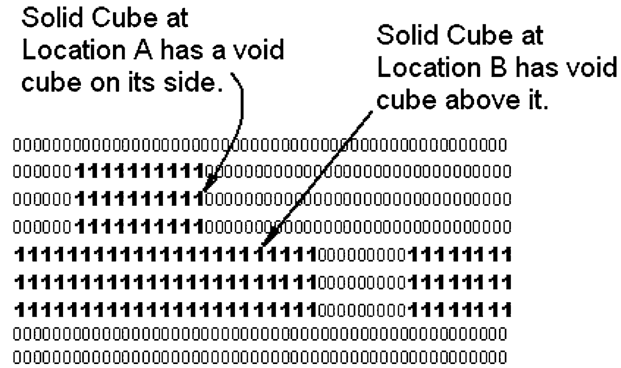


Fig. 19 Illustration of "manufacturing requirements" in terms of binary data

The step of connecting adjacent layers is parallel to the "complete" step used in the work of Vandenbrande and Requicha (1993). Their feature recognizer determines the largest non-intruding volume by sweeping the feature hint found in the earlier hint production stage to recognize features that form the machining volumes.

The feature recognition approach described here is limited to bosses and holes parallel to the direction of mold closure. Nevertheless, this does not impede its use for manufacturability analysis for molding and casting. Holes and bosses must be recognized to determine the subsidiary complexity of step EE of the global algorithm of Fig. 2. With a given direction of mold closure, only the holes and bosses parallel to this direction affect the subsidiary complexity and hence only their recognition in a parallel direction becomes critical. Bosses and holes that are present at an angle are classified as undercuts.

The third step is to check the features obtained in the previous step. For a given feature, boundary solid cubes indicate its boundary. The relative spatial arrangement of boundary solid cubes is used to determine feature validity, shape, and parametric information.

For the part shown in Fig. 15, the boundary solid cubes of the boss lie on a circle. The MEA extracts topological information (information of how one boundary solid cube is located relative to another) from the boundary of the feature formed in step 2. For example, the MEA uses the co-ordinate locations of three randomly chosen boundary solid cubes (these boundary solid cubes belong to the same "clubbing") and finds the equation of the circle passing through them. Further, if more than 80% of the boundary solid cubes belonging to that particular clubbing lie inside an annular ring (inner radius = 0.9 times the radius of circle; outer radius = 1.1 times the radius of circle), then the MEA classifies the feature as the one with a circular cross-section. Note that the percentage of boundary solid cubes that need to lie inside the annular ring and dimensions of the annular ring depend on the size of mesh chosen for the 3D binary representation. To check feature validity, a determination is made if all interior solid cubes are inside a boundary of boundary solid cubes. Last, the MEA evaluates geometric data such as radius of boss, height of boss that are needed to determine the impact of that feature on part manufacturability and cost.

Holes are recognized by a similar but inverted approach as that used to recognize bosses. To find holes, the MEA uses the club, connect and check steps on void cubes rather than solid cubes. Void cubes are classified into interior and boundary. Interior void cubes are void cubes surrounded by void cubes on all six sides. Boundary void cubes are those surrounded by void cubes on some sides and solid cubes on the remaining sides.

The boss and the hole present on the part shown in Fig. 15 were recognized by the MEA as shown in Fig. 20. Figure 20 shows a wire-frame model of the part with the boundary solid cubes of boss and the boundary void cubes of the hole shown by dark shades.

The approach developed here for hole and boss recognition has some similarities and differences with the ASVs approach (Woo 1982). Using the part shown in Fig. 21, we briefly point out the differences between the MEA and the ASVs approach (Woo 1982). The ASVs approach (Woo 1982) consists of computing the convex hull of the part and then subtracting the part from its convex hull to obtain the feature present. Carrying out such an operation on the part shown in Fig. 21 gives the part shown in Fig. 22, which is nothing but the hole recognized from the part.

Our approach represents the part shown in Fig. 21 by a 3D binary array. The uppermost layer of this binary array is the same as that shown in Fig. 16. Here, the black-colored dots stand for void cubes and the gray-colored dots for solid cubes. The MEA clubs the void cubes to form five such layers and then connects them to form a feature that would be recognized as a cylindrical hole. This process is depicted in Fig. 23.

If the ASV approach (Woo 1982) were applied to one layer at a time for each of the five layers, it would produce a recognized hole as output. What the ASV approach (Woo 1982) achieves by subtraction of the part from its convex hull is achieved by the MEA by first representing the part in a binary form and then clubbing together adjacent 0 s. Thus, the MEA can be considered as a layer-by-layer application of the ASV approach (Woo 1982), but it is different from the ASV approach (Woo 1982) in that it uses a 3D binary array to represent the part geometry. The use of binary representation for extracting features in MEA has specific advantages when applied to molding or casting operations because the binary representation allows simple procedures to determine the parting surface and the overall

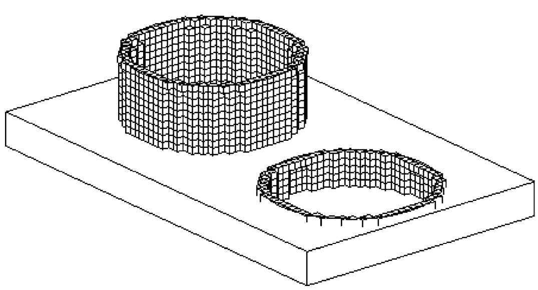


Fig. 20 Recognized hole and boss

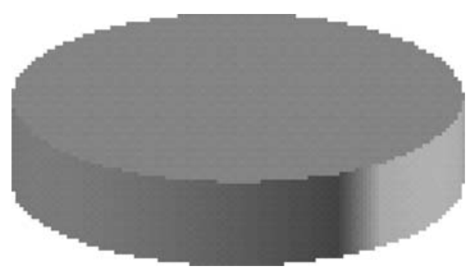


Fig. 22 Recognized hole

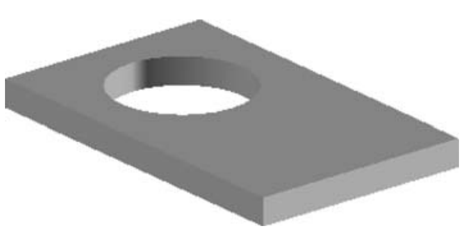


Fig. 21 A simple part with a hole

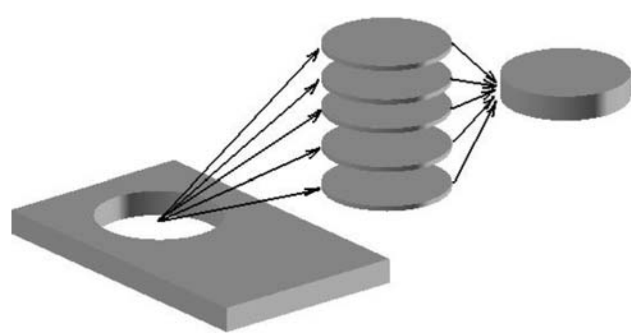


Fig. 23 A graphical comparison between MEA and ASV approach

manufacturability of a part based on access to boundary solid cubes.

An important issue that needs to be addressed at this point is the size of the cube or binary mesh that was used to digitize the solid model. The finer the digitizing mesh, the better the results of the MEA. In order to recognize a boss with a radius of 10 mm, the digitizing mesh should at least be 1 mm $\times$ 1 mm $\times$ 1 mm. As the mesh size becomes larger, the probability of missing a feature increases. The mesh size needed by the MEA depends on the size of manufacturing capabilities and the size of the smallest feature that needs to be recognized. Thus, the MEA needs knowledge about the smallest feature size in order to determine the smallest correct mesh size. A manufacturing engineering or a mold designer provides such knowledge. For example, due to manufacturing constraints, it may not be possible to die-cast a part with a wall thickness < 12.5 mm. Such information related to the basic capabilities of the injection-molding or die-casting processes, which is typically used to answer the yes or no question about manufacturability, also dictates the size of the smallest manufacturable feature and can be used as a guideline for deciding the mesh size.

8.5 Determining the direction of mold closure

The results presented in this article so far address the problems of finding the parting surface of a part, the parting line for a part and recognizing the holes and the bosses present on a part. Determining the direction for mold closure is another key task for automated manufacturability analysis of injection-molded and die-cast parts. The feature recognition methods developed above rely on a pre-specified direction of mold closure, and in turn can be used in an iterative or inverse fashion, to find the preferred direction for mold closure.

In general, parts have bosses, holes, recesses, inserts, and other features that are oriented at arbitrary angles. The direction of mold closure is dictated by the orientation of these features. Specifically, from the expanded algorithm for step BB of the global algorithm, it is apparent that the direction of mold closure is usually the direction of the principal recess (Dixon and Poli 1995). In general, it is desirable that the principal recess gets manufactured by the motion of the principal core. The motion of the principal core in some direction other than the direction of mold closure increases the tooling cost. Thus, finding the direction of the principal recess yields candidate directions for mold closure. Based on the methods developed in this article, hole-type recessed features can be used to determine the direction of mold closure.

Assuming that the principal recess is present at some arbitrary angle to an initial and arbitrary coordinate frame, the need is to determine that angle. First, the part is reduced to the binary representation. Next, a hemispherical mesh is built around one half of the part. Because of the symmetry of mold closure, only one-half of the complete orientation space needs to be searched. This hemispherical mesh is shown in Fig. 24. On this mesh, any arrow directed toward the center of the dome and passing through a point on this mesh is a potential direction of mold closure.

For a recess to be manufacturable by the primary mold-closing action, it must be aligned with the direction of mold closure. Figure 25 depicts the difference between a hole feature that is aligned with the direction of mold closure and one that is not. In the left side of Fig. 25, the boundary cubes at locations A and B lie opposite to each other and are both accessible to the core from the top direction. In the right side of Fig. 25, opposing cubes at locations A and B are not accessible from the same direction i.e., although point A can be reached by the mold core, point B is inaccessible. An important observation is that: when a hole is "aligned" with the mold core, the opposing boundary cubes forming that hole are accessible from the same side.

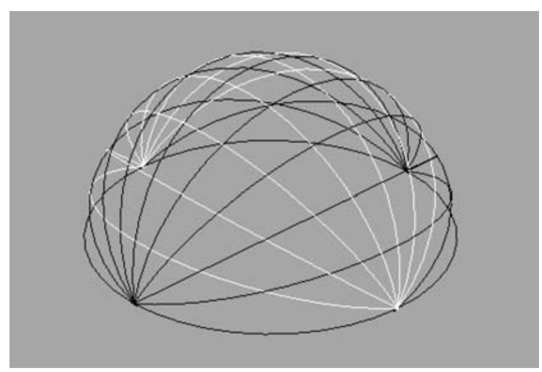


Fig. 24 The hemispherical mold closure direction search space

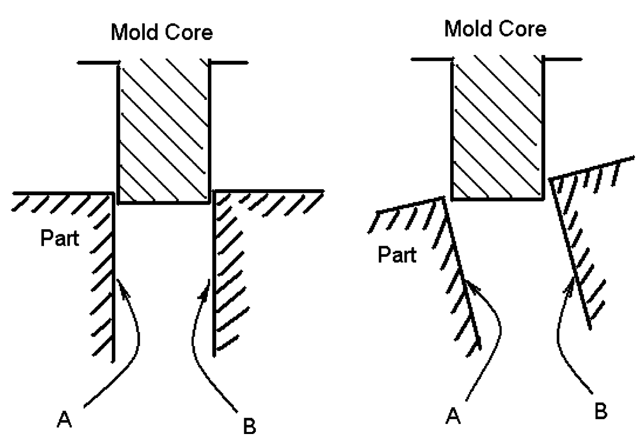


Fig. 25 Finding direction of mold closure

The logic of finding the optimal direction of mold closure is as follows: travel around the part and keep track of the number of opposing boundary cubes accessible from the same direction. When this number is maximized, we have reached the direction of the largest hole and hence have reached the optimal mold closure direction.

Searching through the hemispherical space of possible mold closure directions, the MEA moves to a point on the dome-shaped mesh, builds the 3D binary array for that particular direction of mold closure, and then counts the number of opposing boundary cubes accessible from the same direction. Wherever this number is maximized is the optimal direction. At this optimal direction, the MEA performs a quick "yes" or "no" manufacturability check as discussed earlier. If the answer is "yes", the MEA finalizes this direction as the optimal direction. Otherwise, the MEA moves to the next best direction and so on.

The left side of Fig. 26 shows a part that has a hole oriented at 45° to a proposed direction of mold closure. For this direction of mold closure, the hole is not recognized as a hole feature, but as an undercut. As the MEA searched through space of possible mold closure directions, at 45° the number of opposing boundary cubes accessible from the same direction is maximized. At the 45° angle, the part can be formed by a single mold action; thus, this is the preferred direction of mold closure. The preferred direction of mold closure is shown by the arrow in the right portion of Fig. 26.

The hemispherical search space shown in Fig. 24 corresponds to infinite possible directions of mold closure. However, the MEA in its present state does not check all these possibilities. The MEA explores only a finite number of directions by choosing a finite number of uniformly spaced directions that span over the hemispherical domain. A better approach toward reducing the search space from infinity of possibilities to a finite number is beyond the scope of this article and remains as future work.

The literature on direction of mold closure primarily uses the approach of visibility maps to find all possible undercuts and then finds the optimal direction which minimizes the number of undercuts. Again these methods are "rule-based" methods that process B-rep models. The MEA uses a voxel representation. The method presented in this article is thus a method of finding the optimal mold closure direction by starting with the voxel representation. A comparative study with regards to the computational speed of both these methods is beyond the scope of this article.

8.6 Summary example

A brief discussion on how the MEA performs automated manufacturability analysis of injection-molded and die-cast parts is given next. This discussion is done for a die-cast part shown in the left portion of Fig. 27. This part is a tri-square assembly and is a common device used in the machine shop to measure and maintain right angles between any two assembled parts.

The right portion of Fig. 27 shows the solid model of the part. The actual part has two holes present at location X and location Y. These holes are machined later on the part and are not produced by die-casting. Therefore, these holes are not modeled in the solid model of the part. The part in Fig. 27 has four hole features. Hole feature A and hole feature B are shown in Fig. 27. The hole feature C is formed due to the surrounding walls. One hole feature identical to feature C is present on the bottom side of the part. Thus, the part has a total of four hole features. No boss features are present on the part. The direction of mold closure is along the direction of the largest hole feature i.e.,

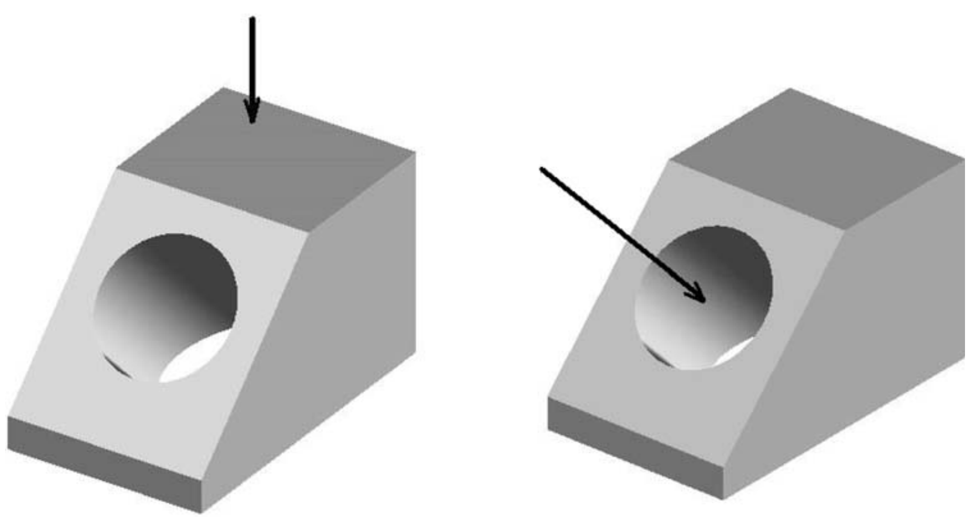


Fig. 26 Demonstration of the MEA finding the direction of mold closure

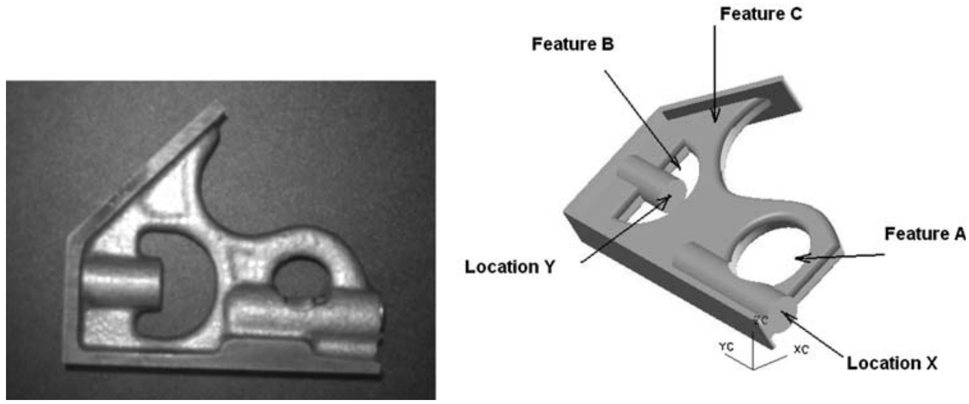


Fig. 27 A die-cast part and its solid model

along the hole feature A. The dimensions of the basic envelope are 60 mm × 55 mm × 11 mm. The part is flat. The part does not have any external and internal undercuts and the parting surface is planar.

It should be noted while building the solid model of the part; it is intentionally tilted by a 30° rotation about the Y-axis. While testing the part, it is expected that the MEA will recognize the correct direction of mold closure to be along the hole feature A. This part will also test the MEA's ability to recognize holes or depressions present on the part. The MEA extracts the following information from the 3D binary array.

1. The direction of mold closure is along the hole feature A. This is shown in the left portion of Fig. 28. After the MEA gives the correct direction of mold closure, the 3D binary array is again built for this new orientation. Further testing is carried out on this new 3D binary array.
2. No undercuts are found on the part. The parting surface is planar and the parting line as found by the MEA is shown in the left portion of Fig. 28.
3. Four hole features are recognized on the part. The hole features are shown in the right portion of Fig. 28.

9 Implementation

The MEA is implemented using a combination of C ++ language, UG® Open API and UG® Open GRIP® (UniGraphics Solutions Inc 2001). The solid models of the test parts are constructed using the solid modeling package Unigraphics®. The codes for converting this solid model representation into a "voxelized" form are written using UG Open Grip. The running times for the Grip® codes vary between 2 min for simple parts in Fig. 13 to approximately 8–10 h for larger and complex parts like the one shown in Fig. 1. Voxelizing a given solid model is the slowest part of implementing the MEA. However, there are commercial packages available for voxelization that run more quickly. Such packages would be used for any commercial implementation of the MEA. At the end of this "voxelization" step, Grip writes the binary array representation of the part to a text file called "3d_array".

Programs written using C ++ language then process the binary data written in the text file "3d_array". First the MEA finds an optimal direction of mold closure. The time taken for this step varies between 2 and 10 min depending

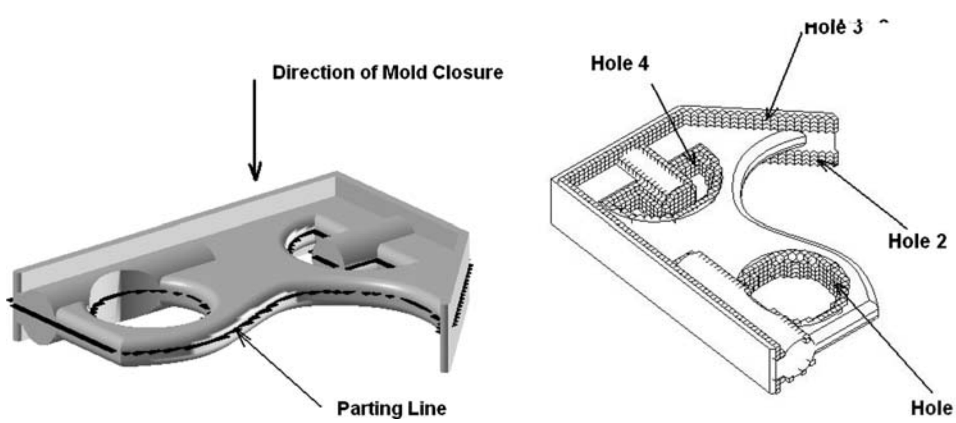


Fig. 28 The direction of mold closure, the parting line and the holes as recognized by the MEA

on the size of the parts. (It is directly proportional to the size of the binary array). For example, it took approximately 3 min to find the optimal direction of mold closure for the part in Fig. 27. Once the optimal direction is found, the part is oriented along the optimal direction and the results of the voxelized model along this direction are written to a new text file called "3d_array_optimal". Now the MEA needs to find the parting surface, the undercuts, the holes and the bosses on the part. Each one of these is found by running a separate C ++ code, which reads from the text file "3d_array_optimal", generated earlier and gives the output in less than a minute. The outputs of each of the C ++ codes (i.e., number of holes found, boundary cubes that build the recognized holes etc.) are written to another text file called "results". Finally, a C ++ program which implements the Dixon and Poli (1995) logic (i.e., the global algorithm of Fig. 2) reads the text file "results" and reports the manufacturability of the part in terms of its tooling cost in dollars.

As a final step, the recognized parting surfaces, undercuts, recognized holes and bosses need to be displayed on the solid model of the part. As a designer, one would certainly want to verify whether the MEA is recognizing the features correctly. Toward this end, UG Open API codes read the output of the hole recognition program and actually draw the boundary cubes of a recognized hole in Unigraphics. This display is superimposed on the actual part and the output is of the form as seen in Figs. 20, 28, and others.

10 Future work

The work presented in this article makes key contributions to automated manufacturability analysis of injection-molded and die-cast parts. Nevertheless, the problem of automatically evaluating the manufacturability for the entirety of injection-molded and die-cast parts remains an unsolved problem. A set of rules to operate on the 3D binary data with the motivation of recognizing walls, complex features such as ribs, and several other features needs to be formalized and established. To make these rules as general as possible with simultaneous consideration of the finiteness and efficiency of the set of rules is an area of future work. These sets of rules will be tested on a range of injection-molded and die-cast parts and their validity will be established.

The feature recognition algorithm implemented here has not addressed robustness with respect to noise in the input model. Before the approach presented here can be said to be fully mature, noise, and robustness need to be addressed. Noise can become a problem in solid models as different formats are exchanged or models have been reduced to point cloud representations rather than feature based models. In the examples presented here, noise is insignificant because binary decompositions were developed directly from the solid model.

A long-term goal for automated manufacturability analysis is that upon query, the system can return suggestions on part redesign. For example, after reporting the manufacturing cost for the existing design, the MEA would report what features affected the cost the most. Further, the MEA would give suggestions for re-orientation or removal of the features that would reduce the cost of the existing design. Such redesign suggestions would impart a real meaning to the phrase "computer-aided design." However, before these "automated synthesis" type of activities can be developed, the "automated analysis" activities need to be solved completely.

11 Conclusion

This paper discusses a method for automatically evaluating the manufacturability of injection-molded and die-cast parts from their solid models. One key contribution of this work is the development of a complete algorithm that, with the solution of all the required feature recognition problems, will enable the automation of manufacturability analysis. The second key contribution is the solution of some of the required feature recognition problems. The framework for feature recognition presented here derived its inspiration from the physics of the molding and casting processes. A novel concept of using elemental cubes to evaluate manufacturability of the part and using the same binary representation to extract high-level feature information was provided. Specifically, the MEA solves the problems of finding the parting surface, parting lines, hole recognition, boss recognition, and finding the mold closure direction. Finding the parting surface has specific impact to injection-molding and die-casting. The feature recognition of holes and bosses extends to other manufacturing processes. The work reported here extends the existing knowledge in "feature recognition for automated manufacturability analysis" to the domain of non-material removal processes.

Appendix: Expanded algorithms for steps BB, CC, DD, and EE of the MEA

See Figs. 29, 30, 31, 32.

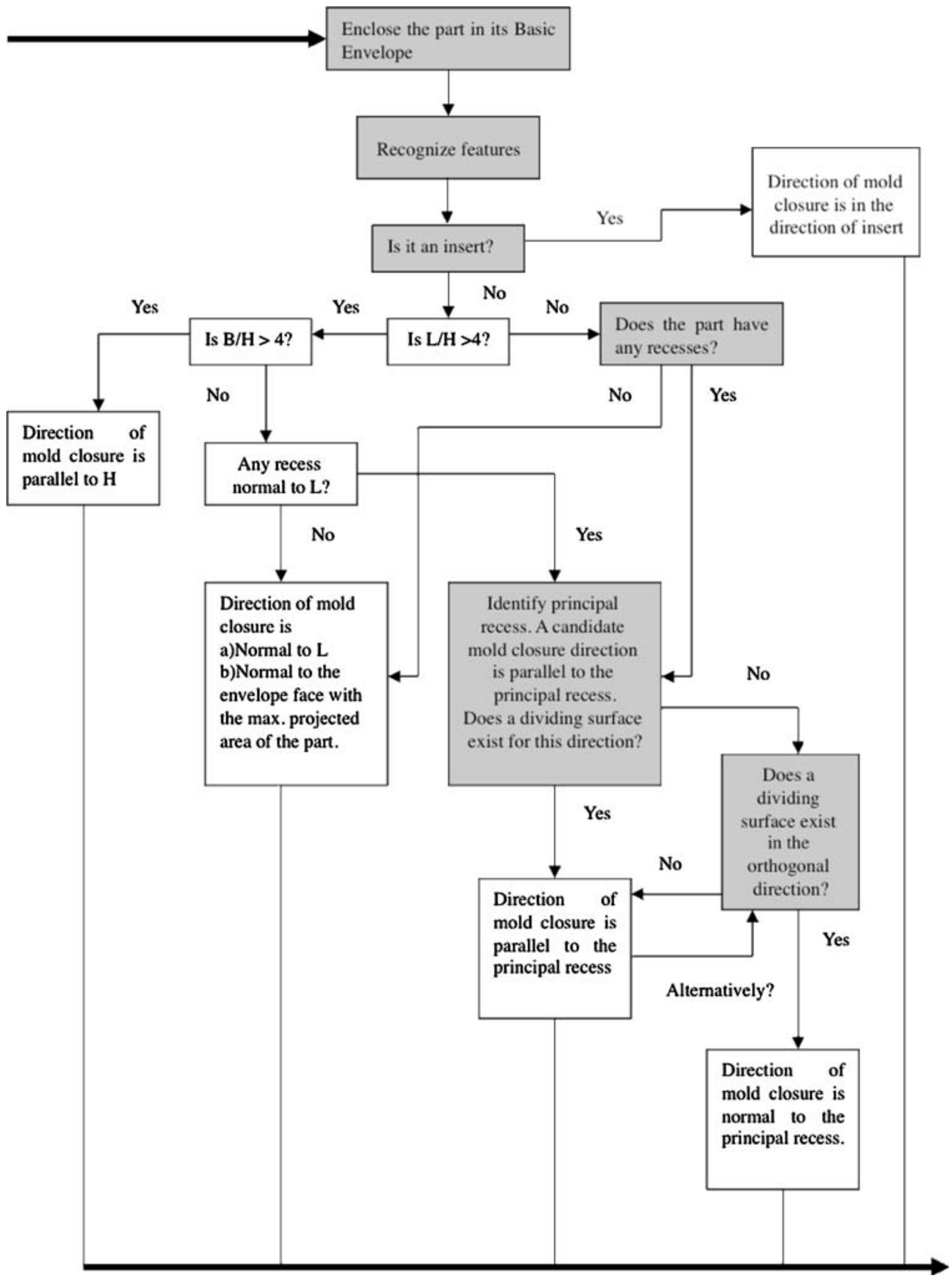


Fig. 29 Expanded algorithm for step "BB" of the Global Algorithm

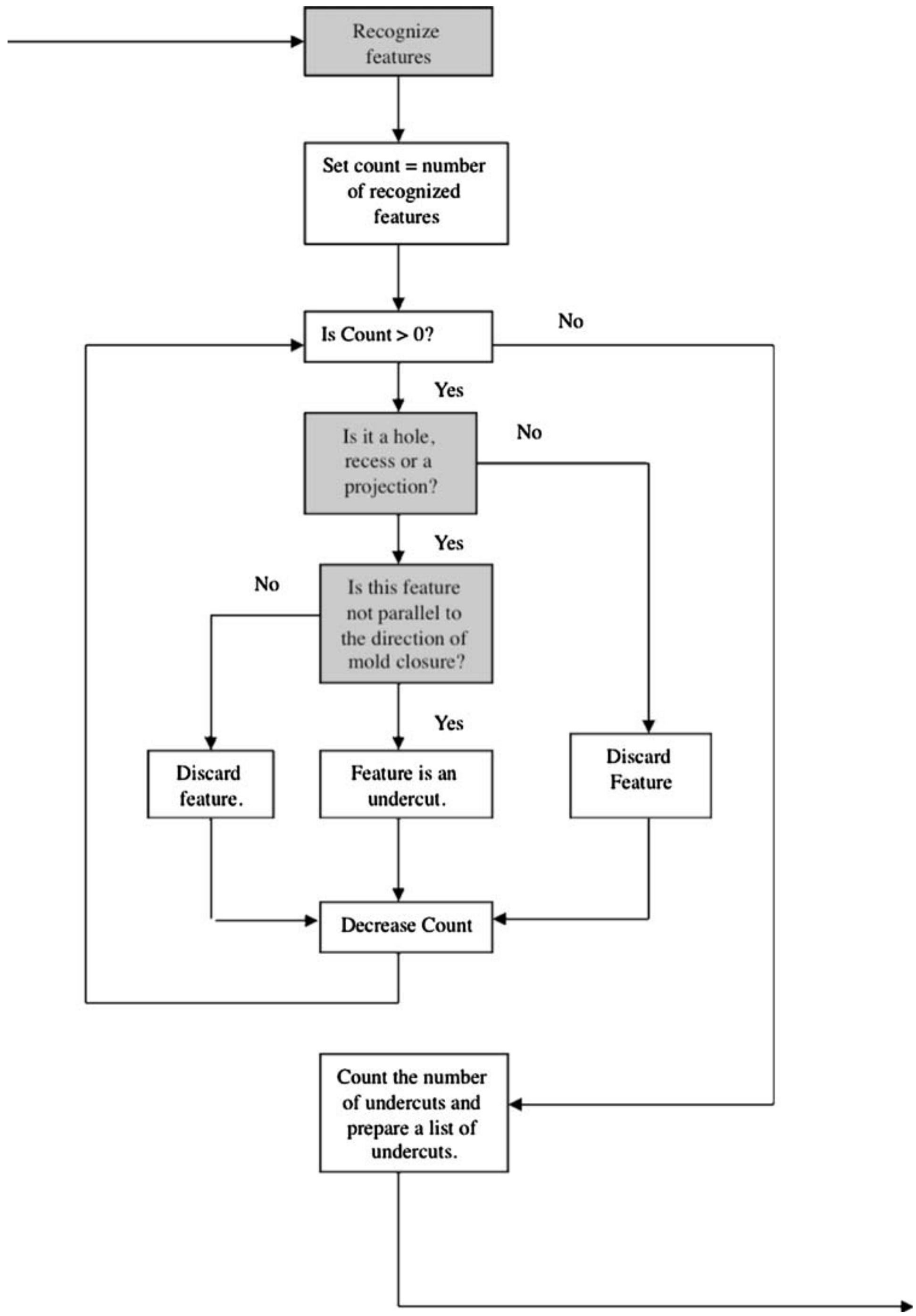


Fig. 30 Expanded algorithm for step "CC" of the Global Algorithm

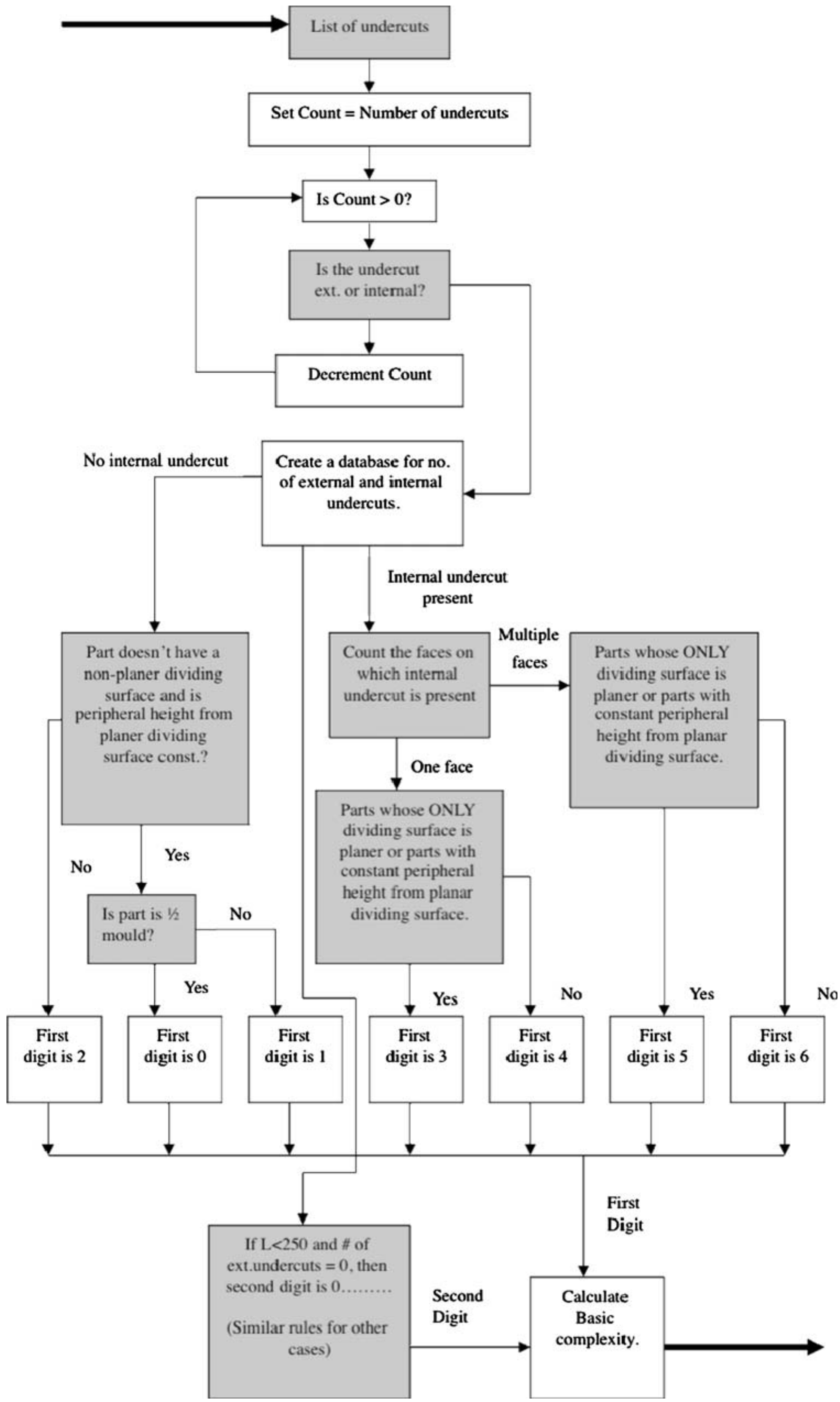


Fig. 31 Expanded algorithm for step "DD" of the Global Algorithm

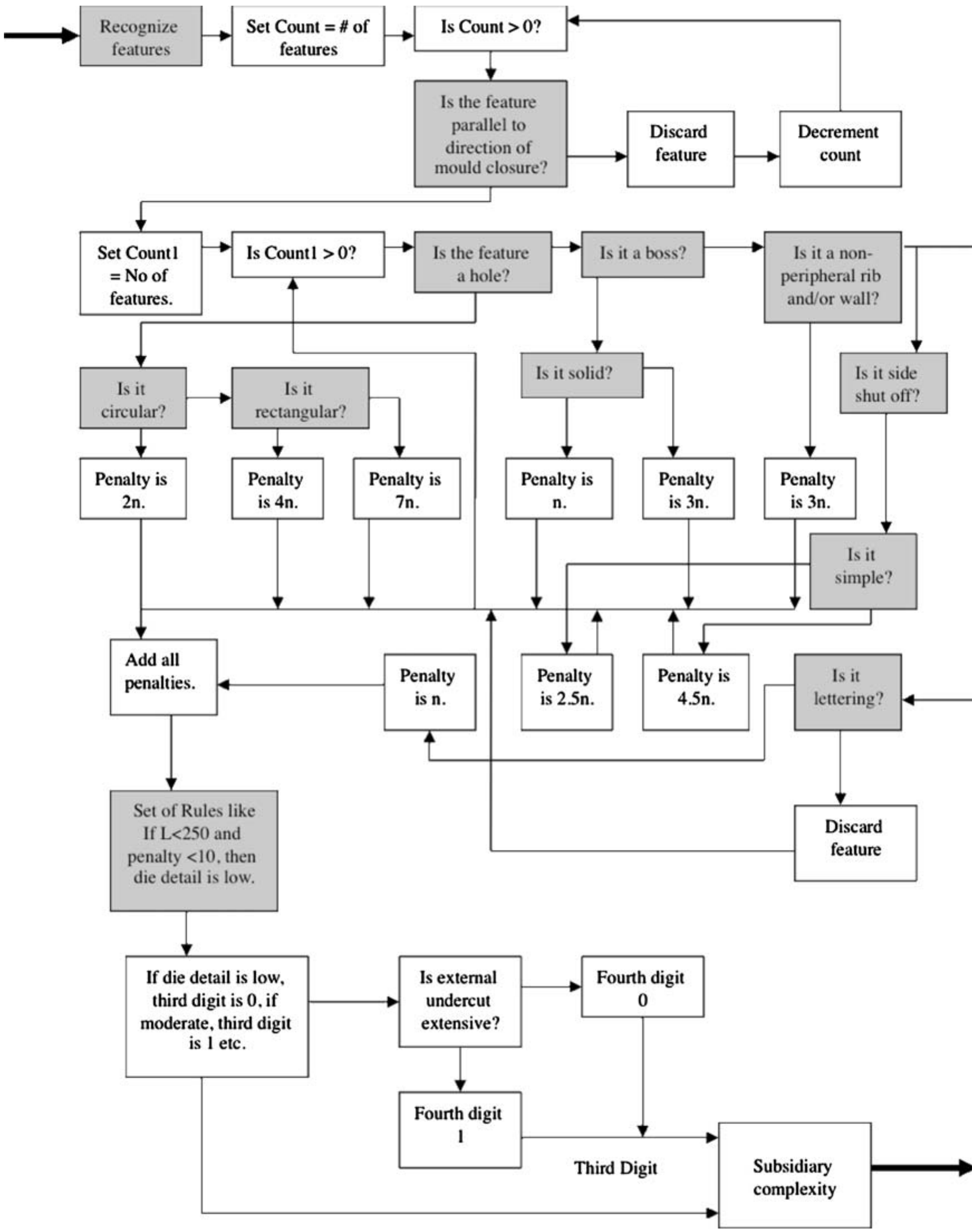


Fig. 32 Expanded algorithm for step "EE" of the Global Algorithm

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