FEATURE RECOGNITION FOR INJECTION-MOLDED AND DIE-CAST PARTS

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ABSTRACT
In this article, a framework to perform the computer-aided Design for Manufacturability analysis of injection-molded and die-cast parts is presented. The framework includes an implemented algorithm to solve key outstanding challenges in feature recognition for manufacturability analysis. The proposed feature recognition algorithms operate on a 3D binary array obtained from the solid model of the part. Solutions to the feature recognition problems of finding the best direction of mold closure, finding the mold parting line of the part and determining planarity of the parting surface is presented in this article. The feature recognition algorithms presented here are validated through application to several test parts. The algorithms proposed here recognize the direction of mold closure, the primary mold parting surface, undercuts, holes, and bosses present on the part. In addition, an estimated part mold cost is calculated by the algorithm.

Keywords: Design for Manufacturing, Feature Recognition, Automated Manufacturability Analysis, Injection-Molding, Die-Casting

INTRODUCTION
Computer-based tools that attempt to automate the Design for Manufacturing (DFM) analysis are a result of considerable research in the areas of DFM, computer-aided design (CAD), and feature recognition. Developing methods to enable automated DFM analysis for the common and important manufacturing processes of injection-molding and die-casting is a basic contribution to design for manufacturing. The Manufacturability Evaluation Algorithm (MEA) proposed by McAdams and Bidkar [1] is a computer-based tool that performs the DFM analysis of injection-molded and die-cast parts. In the previous effort, several important feature recognition problems were addressed. The current article continues to contribute solutions to feature recognition problems for injection-molding and die-casting. Also, the current article validates the MEA presented in [1] by demonstrating its applicability on a range of injection-molded and die-cast parts.

The next section presents a literature survey in the areas of DFM, computer-aided design and feature recognition for automated DFM analysis. Following that, there is a brief introduction to the MEA. How the MEA finds the best direction of mold closure for a part is discussed next. The next section discusses the solution to the feature recognition problem of finding the parting line and deciding whether or not the parting surface is planar. How the MEA finds whether or not the part can be molded in one half of the mold is discussed next. The MEA presented in this article is validated by demonstrating its use on multiple test parts. Finally, two examples to real and more complex parts are shown. Lastly, there is brief discussion of future work and conclusions.

RELATED WORK
DFM is a broad area of engineering practice and research with many techniques and approaches [2-5]. Manufacturability evaluation and feature recognition are two critical DFM areas. A comprehensive survey of various manufacturability evaluation approaches can be found in the work of Gupta et al. [6]. Poli et al. [7-10] present DFM guidelines for designing injection-molded and die-cast parts during the configuration and parametric stages of design.

The current geometric modeling techniques use boundary representation (B-rep) [11, 12]. Rather than high-level feature information, the data stored in the B-rep model of a part is in the form of points, edges and faces. The field of feature recognition has emerged from the need to extract high-level feature information from B-rep models. Recognizing part features from a solid model has been the area of active research for at least the past 20 years. Henderson et al. [13] have surveyed the various feature identification techniques used to extract features from B-reps of parts. The rule-based approaches [14-16] use sets of feature rules to extract feature information from the geometric data. The existing feature
recognition methods like the rule-based system [14-16] operate on a large amount of geometric data consisting of points, edges, and faces. The large volume of data tends to reduce the speed of these algorithms. The application of the existing feature recognition techniques is limited to features with over-simplified geometries. Existing feature recognition techniques can recognize 2.5 dimensional features. 2.5-dimensional features are those that have a constant cross section along the third dimension.

The graph-based approach [17, 18] uses the graph theory and the techniques of sub-graph matching to recognize features from the solid model. The application of existing feature recognition techniques of graph-based systems [17, 18] is limited to single features. These approaches have difficulty handling intersecting features.

Neural networks have been applied to the problem of feature recognition in the work of Prabhakar [19]. Woo [20] developed the alternating sum of volumes approach in his pioneering work in the field of feature recognition. Kramer et al. [21] created a library of material removal shape element volumes (MRSEVs).

Regli et al. [22-24] 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. The delta volume is thus decomposed into MRSEVs and this database is used to evaluate the manufacturability in the context of machining. Due to the basic differences in machining and molding or casting, the approach of extending machining oriented methods such as Regli’s to molding and casting is unclear.

Requicha and Han [25] 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 [26] 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 [27] use 3D wavelet transforms for the extraction of form features from the CAD model of a part.

Dhaliwal et al. [28] develop a feature based approach to the automated design of multi-piece sacrificial molds. Their approach uses sacrificial mold pieces to handle accessibility problems in molding. Currently, their approach is limited to parts constructed from a limited set of geometric parts.

Yin and Xiong [29] develop a moldability analysis approach based on feature recognition and geometric reasoning. Their approach recognizes undercuts through an alternating sum of volumes (the regularized decomposition between the part and its convex hull). Using this approach undercut features are recognized. Their method then proposes a direction of mold closure direction that results in the minimum number of undercut features.

Majhi et al. [30] develop a method that suggests a mold parting line for a convex polyhedron. Their approach searches for the best parting line based on several flatness criteria. Chen and Rosen [31] develop a method to design multi-piece molds. Their approach is based on the convexity and concavity of part faces.

Ravi and Srinivasan [32] support mold design through the development of computer-aided method for parting surface design. Their approach requires interactive input from the designer to identify potential parting planes and features.

Fu et al. [33] develop a method for the automated recognition of undercut regions for injection mold design. Their approach is based on edge and surface topography of the part. Nee et al. [34] develop an automatic method for determining parting lines and surfaces for injection molds. In some cases, their approach requires manual input. The parting line and surface is that which requires the least side cores for a given direction of mold closure. Hui [35] develops an automatic method to assess the moldability of a part. Hui’s approach is based on access to surfaces. The method includes the analysis of the motion of the mold as it assesses the potential of split cores to mold internal undercuts.

THE MANUFACTURABILITY EVALUATION ALGORITHM

Important issues in automated analysis of injection-molded and die-cast parts have been addressed. Nevertheless, a complete and efficient solution has not been developed. The approach developed in [1] and extended below differs from those reviewed above in that it doesn’t explicitly use the topology of part surfaces and edges to assess part manufacturability. Rather, the part is decomposed into small elements and the accessibility and relationship of these elements is used to perform feature recognition and part manufacturability.

The bottom right corner portion of Figure 1 shows the 3D binary array representation of the part shown in the upper left portion of Figure 1. The MEA represents the solid model of a part using two types of rectangular cubes. The dark colored cubes in Figure 1 represent solid cubes and the grey-colored cubes stand for void cubes. Using such a 3D binary array representation, the problem of evaluating the manufacturability of the part reduces to evaluating the manufacturability of individual solid cubes that form the building blocks of the 3D array [1].

![Figure 1. Decomposing the part into a 3D binary array.](image)

Also, to determine part manufacturability the approach developed in [1] is based on using the empirical knowledge
cataloged by Dixon and Poli [7] rather than explicitly attempting to reason through a sequence of mold geometries and motions that could create a feature or part. By assessing part moldability based on empirical knowledge about the moldability of part features, it is hoped that the moldability reasoning algorithms can be simpler and decrease computation time.

McAdams and Bidkar [1] have demonstrated the use of such a 3D binary array for determining the parting surface of the part, recognition of undercuts, and recognition of holes and bosses. In the present article, the solution to the more general problem of finding the best direction of mold closure from the 3D binary array is given. Also, this article focuses on the problem of finding the mold parting line for the part.

**USING THE MEA TO FIND THE DIRECTION OF 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. In general, the preferred direction of mold closure is parallel to the principal recess [7].

Depending on how a part solid model is developed, the principal recess can be at any orientation with respect to some working or global coordinate system. For the part shown in the top of Figure 2, the principal recess is present at an angle of 45 degrees with some initial trial direction of mold closure. This direction is shown by an arrow in Figure 2. The MEA converts the solid model of the part in Figure 2 into a 3D binary array, which is aligned with this initial trial mold closure direction.

The first step is to obtain the 3D binary representation that is aligned with the initial mold closure direction (Note that in Figure 1, every cube in the 3D array is aligned with the XYZ coordinate system and hence it can be said that the 3D array is aligned). Next, a hemispherical mesh is built around one half of the part. The hemispherical mesh shown in Figure 3 is the search space for the direction of mold closure. On this mesh, any arrow directed towards the center and passing through a point on this mesh is a potential direction of mold closure. The MEA moves through the hemispherical mesh and performs a test to evaluate the goodness of that potential mold closure direction. The test is based on the manufacturability of the primary recess or hole at different orientations, or positions, in the hemispherical search space.

As shown in Figure 4, for a recess or hole to be manufacturable by the basic mold-closing action, it must be aligned with the direction of mold closure. In the left portion of Figure 4, the boundary cubes at locations A and B lie opposite to each other and are both accessible to the core from the top direction. The boundary cubes at location A and B form an accessible opposing boundary cube pair. In the right portion of Figure 4, opposing cubes at locations A and B are not accessible from the same direction. These boundary cubes represent a recess that cannot be manufactured by the primary core motion for that particular mold closure direction.

**Figure 3. The hemispherical mold closure direction search space.**

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 accessible opposing boundary cubes pairs. The MEA checks whether or not these pairs lie on the boundary of a void. The bottom portion of Figure 2 shows an invalid opposing boundary cubes pair formed by solid cubes at location A and B. In the bottom portion of Figure 2, two opposing boundary cubes at location C and D are separated by a void and are thus a valid pair. The location in the search space for which the number of accessible opposing boundary cubes is maximized corresponds to a mold closure direction that is parallel with the

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Figure 2. Boundary cubes at location A do not relate to a principal recess. The hole at location B has boundary cubes at C and D with a void between them that indicate a potential principal recess.
primary recess and thus the direction of mold closure is identified. To ensure that the proposed mold closure direction corresponds to a primary recess that is a valid feature, hole recognition methods are used from [1].

![Diagram of mold core and part](image)

**Figure 4.** An Illustration showing the alignment requirement of the mold core and part primary recess.

For parts that do not have clear recess features, the MEA uses the guidelines from Dixon and Poli [7] to determine the best direction of mold closure. For example, if the part has no holes, and if it is flat shaped, then the direction of mold closure is along the height of the part. Similarly, if the part has no holes, and if it is box-shaped, then the direction of mold closure is a) normal to the length of the part and b) normal to that face of the part that has the maximum projected area.

**USING THE MEA TO FIND THE PARTING LINE OF THE PART**

Liou and Miller [36] have reported a user-interactive platform where the user chooses the parting surface and the parting line of the die-cast part being designed. However, if the DFM analysis process is to be completely automated, then the computer should be able to recognize the parting surface and the parting line of the part. McAdams and Bidkar [1] describe a MEA where the computer finds the parting surface of injection-molded and die-cast parts. In the present article, the MEA’s ability to find parting surfaces is further extended to finding the parting line of the part. Once the parting line of the part is known, the MEA can decide whether the parting surface is planar and whether or not the part lies in one half of the mold, information needed to determine mold cost.

![Diagram of generation of parting surface](image)

**Figure 5.** Generation of the parting surface.

The left portion of Figure 5 shows a simple die-cast part and the right portion of Figure 5 shows its upper parting surface as generated by the MEA. The lower parting surface is the bottom of the part. The upper parting surface is formed by the upper half of the mold cavity. The lower parting surface is formed by the lower half of the mold cavity. The parting line is the line where the upper and lower parting surfaces meet.

To determine the parting line, the MEA moves along the periphery of the part and constructs the parting line where the upper and lower parting surface meet. For example, at location A in Figure 6, the upper parting surface formed by the upper circular surface of the boss and the lower parting surface formed by the lower circular surface of the boss meet each other. Using the binary decomposition of the part simplifies determining this parting line. The parting line is at the solid cubes on the upper and lower parting surface with the same Z-coordinate.

![Diagram of generation of parting line](image)

**Figure 6.** Generation of the parting line.

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 can lie anywhere between the upper and the lower parting surface. For example for a solid cube at location B in Figure 6, the upper parting surface lies at location D and the lower parting surface lies at location C. The parting line at location B can lie anywhere between the Z-coordinates of locations C and D. Planar parting surfaces generally result in a less expensive mold, thus the MEA attempts to create a planar parting line. The parting line at location A is constrained by the geometry of the boss and the physics of the molding of the process. Thus, the MEA locates the parting line between location C and D in the same plane as the parting line required at location A. The left portion of Figure 7 shows the planar parting line generated by the MEA for the part shown in Figure 6. The result is a planar parting line that accommodates the different boss features of the part.

The right portion of Figure 7 shows a part for which a planar parting line is not practical. In developing the parting line for this part, the MEA first constructs a parting line at location A because the upper and the lower parting surfaces meet there. At location B, there is no valid parting line that is in
the same plane as the parting line at location A. As a result, the MEA constructs a separate parting line which lies halfway between the upper and the lower parting surfaces at location B.

With the parting line determined, assessing planarity is simple. If the parting line has the same Z-coordinate over the whole periphery of the part, then the MEA considers the parting surface to be planar. To implement the DFM methodology of Dixon and Poli [7], the recognition of a planar parting surface needs to be combined with the recognition of a constant peripheral part height. For this assessment, the MEA needs to recognize a peripheral wall feature. Currently, the MEA does not recognize peripheral walls. The recognition of peripheral walls remains future work.

**Figure 7. Planar and non-planar parting lines.**

**USING THE MEA TO FIND WHETHER THE PART LIES IN ONE HALF OF THE MOLD**

Mold costs are influenced by the amount of machining that must be done to create the core and cavity hollow sections. Parts that can be molded in one half of the mold are cheaper to manufacture [7]. Shown below in the left portion of Figure 8 is a part that can be molded in one half of the mold. Both halves of the mold need to be machined when manufacturing the part in the right portion of Figure 8. If no particular restrictions on the location of parting line are present in the part (restrictions get dictated at locations where the upper and the lower parting surface meet), then the MEA constructs a parting line which lies totally on one side of the part. In such instances, the part is considered to lie in one half of the mold. If the MEA encounters parts (parts like the one in the right portion of Figure 8, assuming a direction of mold closure perpendicular to the shaded surface) for which the parting line has to lie within the upper and lower limits of the parts, then the MEA decides that the part does not lie in one half of the mold.

**Figure 8. Parts which can and cannot be molded in one half of the mold.**

**VALIDATION OF THE MEA**

This article presents methods for finding the direction of mold closure, determining the mold parting line, and determining mold parting surface planarity. In previously published work, automated methods were presented for the automated recognition of complete parting surfaces, undercuts, holes, and bosses in the context of injection-molded and die-cast parts [1]. Using Unigraphics solid modeling software and some interface extensions, the recognition algorithms have all been coded in C++. Using this code, the MEA begins with a solid model and first finds the best direction of mold closure. Then, for this direction of mold closure, the MEA finds the parting surface, finds whether it is planar or non-planar, and also recognizes the undercuts, holes and bosses present on the part. In addition, the algorithm develops an estimated mold cost using the methods of Dixon and Poli [7]. Here, the MEA is tested through application to several simple and real parts.

The twelve injection-molded and die-cast parts shown in Figures 9 and 10 are used to test the feature recognition algorithms of the MEA. Part 1 in Figure 9 has one solid boss (feature A) and one hollow boss (feature B). Part 2 in Figure 9 has one solid boss (feature A) and one hole (feature B). Part 3 in Figure 9 has one rectangular hole (feature B) and one internal undercut (feature A). Part 4 in Figure 9 has one solid boss (feature A) and one rectangular hole (feature B). Further in Part 4, the parting surface is planar and due to features C and D, the part does not lie in one half of the mold. Part 5 in Figure 9 has one circular hole (feature A) and one external undercut (feature B). Part 6 in Figure 9 has one solid boss (feature A) and the parting surface is non-planar due to the presence of feature B. Furthermore, for all the six parts shown in Figure 9, the direction of mold closure is vertical.
Figure 9. Test parts used for validation of the MEA.

Figure 10. Test parts used for validation of the MEA. The feature labels for part 12 can be more clearly seen in Figure 14.

The direction of mold closure for the Part 7 in Figure 10 is along the hole feature A. This part has one hole (feature A) and one external undercut (feature B). Part 8 in Figure 10 has three hollow bosses (features A, B and C) and one depression formed by the surrounding wall. This part has a non-planar dividing surface and no undercuts. Part 9 in Figure 10 has five holes and a non-planar parting surface. Part 10 in Figure 10 has four holes (features A, B, C and one hole on the bottom face) and the parting surface of the part is planar. Part 11 in Figure 10 has three holes (features B, C and D) and one hollow boss (feature A). The direction of mold closure is parallel to feature B. Part 12 in Figure 10 has thirteen solid bosses, two hollow bosses and six holes. The parting surface of the part is non-planar and the part has two internal undercuts.

Performing the complete automated analysis of each of the parts, the MEA successfully extracts all the feature information from the solid models of all 12 test parts. After extracting this information, the MEA uses the guidelines in Dixon and Poli [7] and estimates the tooling costs for each of the twelve parts. The tooling costs estimated by the MEA are compared with those estimated by manual DFM analysis and the error found was
negligible (0.02 %). The feature recognition results for two parts are discussed in detail in the following discussion.

![Die-cast part and its solid model](image)

**Figure 11. A die-cast part and its solid model.**

The left portion of Figure 11 shows a die-cast part. This die-cast part is used in a try square assembly. The bottom portion of Figure 11 shows the solid model of the part. The actual part has two holes present at location X and location Y. These holes are machined after casting and are not modeled in the solid model of the part. The part in Figure 11 has four hole features. Hole feature A and hole feature B are shown in Figure 11. 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 4 hole features. No boss features are present on the part. The direction of mold closure is along the hole feature A. The part is flat. The part does not have any external or internal undercuts. The parting surface is planar, but the part does not lie in one half of the mold. Using the method from Dixon and Poli [7], the tooling cost is estimated as $11,690.

To test the ability of the MEA to recognize the correct direction of mold closure, the solid model of the part is tilted by 30 degrees about the Y-axis. The MEA extracts the following information from the 3D binary array:

- The direction of mold closure is at 30 degrees with respect to the vertical.
- No undercuts are found on the part. The parting surface is planar and the parting line as generated by the MEA is shown in the right portion of Figure 12. The part does not lie in one half of the mold.

Four hole features are recognized on the part. The hole features are shown in the left portion of Figure 12. The MEA estimates the cost of the mold the same as a manual analysis of mold cost.

![Recognized holes, parting line and direction of mold closure](image)

**Figure 12. The recognized holes, parting line and direction of mold closure.**

Figure 13 shows a part which forms the base of the computer mouse. This part is manufactured by injection-molding.

![Injection-molded part](image)

**Figure 13. An injection-molded part.**
Figure 14 shows the solid model of the mouse base. The solid model used for analysis has been simplified somewhat, though it still has almost all the features that are present on the actual mouse base. Features D, E, F, G, H, I, K, L, O, P, Q, U, and T are solid bosses. Features S and B are hollow bosses. Features C, V, R form circular holes in addition to two circular holes present on the bottom side of the mouse base. Feature A is a depression or recess formed by the surrounding wall. Feature M and J are internal undercuts. The feature N is a hollow boss. Note that the feature N is not supported fully by the base and is a hanging feature. For the purpose of manual DFM analysis, the feature N will be considered as a hollow boss. Thus, the part shown in Figure 14 has thirteen solid bosses, three hollow bosses, five circular holes and one irregular shaped depression. The part is flat-shaped. The direction of mold closure is along the direction of Feature A. The part has two internal undercuts and both of them are present on the same face. The parting surface of the part is non-planar. Using the methods of Dixon and Poli [7], the tooling cost for this part is estimated as $29,400.

The MEA extracts the following data from the 3D binary array of the injection-molded part. The direction of mold closure is parallel to the vertical direction and along the direction of feature A. Two internal undercuts are found on the part. Both the internal undercuts are present on the same face. The parting surface is non-planar. Two hollow boss features are found on the part. These are shown in Figure 15. Note that feature N in Figure 14, which was considered as a hollow boss during the manual DFM analysis, does not get recognized by the MEA. The reason why the MEA does not recognize this feature is that it is not properly connected to the base and is a “hanging” feature. The boss recognition algorithms of the MEA [1] require a base layer for the boss feature to get recognized. Since the feature N does not have a base layer, feature N does not get recognized by the MEA.

The MEA finds 13 solid bosses on the part. These are shown in Figure 15. 6 holes are recognized by the MEA. The mesh cube size is large compared to two of the circular holes. Therefore the MEA cannot recognize them as circular holes. The recognized holes are shown in Figure 16. The MEA estimates the cost of the mold almost identically to a manual analysis of mold cost.

Figure 14. A solid model of the mouse base

Figure 15. Recognition of bosses.

FUTURE WORK
The work presented in this article makes key contributions to automated manufacturability analysis of injection-molded and die-cast parts. The MEA’s ability to recognize features should be further enhanced by establishing rules for recognition of wall features. Recognizing wall features (both peripheral and non-peripheral) along with recognition of feature patterns like ribs remains as future work.

As presented here, the algorithm requires a mesh size for developing the binary array and a step size for the search through the hemispherical space to determine mold closure direction. Both of these sizes impact the smallest feature that can be recognized by the MEA. Also, these sizes impact the time required to produce a result. In general, developing methods to identify appropriate and variable mesh and step sizes is a challenging problem and remains future work. Nevertheless, in the immediate future, the mesh size can be set based on the capability of the manufacturing process. In other words, by knowing the smallest feature the manufacturing process can produce, an appropriate mesh size can be determined. Though minimum feature size is not included in the knowledge cataloged in [7], it is generally knowable and can be included in the algorithm.
CONCLUSION

This paper is an extension of the work presented by McAdams and Bidkar [1]. One key contribution of the work presented in this article is the development of a new feature recognition technique for finding the best direction of mold closure. Another key contribution is a new solution to the feature recognition problem of finding the parting line. Knowledge of the location of the parting line is further used to determine whether the parting surface is planar and whether or not the part can be molded in one half of the mold. Finally, the application of the MEA on a range of injection-molded and die-cast parts is demonstrated. The MEA successfully recognizes the directions of mold closure, the parting surfaces, the undercuts, the holes, and the bosses from the solid models of the test parts. The MEA’s ability to estimate the tooling cost from the solid model of the part is also demonstrated. Developing a “intelligent” CAD tool which gives redesign suggestions in order to improve the manufacturability of a design is one of the goals of the research presented here. The work presented in this article takes us closer towards the ambitious goal of developing such a tool.

REFERENCES


An immediate goal of this research work is to extend the MEA’s ability to recognizing features as required during the parametric stages of design. Presently, the MEA evaluates parts that are in the configuration stage of design. During the parametric or detailed stages of design, complex feature recognition problems like recognizing rib patterns, slots, groove patterns, designing parts for uniform wall thickness to address such important subtleties of mold design such as uniform cooling of liquid material, and appropriate draft angles need to be addressed. The MEA’s capabilities will be extended to solve these important feature recognition problems.

A long-term goal of the computer-aided DFM analysis tool is that upon query, the tool 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.