








Design Analysis and Modification of Ribs and Tubes on Thin-Wall Parts for Mold Flow Analysis

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Abstract. A DFM analysis and design modification system for plastic injection molding was developed in this study. It mainly included a feature recognition algorithm to extract tube and rib features for analysis, a DFM analysis algorithm for the optimization of feature dimensions, and a design modification algorithm to modify unqualified ribs and tubes automatically. The proposed feature recognition algorithm recognized auxiliary faces, including translation, wall and bottom faces, on the inner surface of a thin-wall part, and then grouped each set of protrusion faces. Tubes and ribs were then recognized with separate recognition algorithms. The proposed DFM analysis algorithm provided a data structure of fillet, rib and tube features for the evaluation of rib and tube dimensions. The optimization of feature dimensions included thickness, height, draft angle, base radius, and space for both ribs and tubes in accordance with various design guides. Finally, the design modification algorithm could modify all unqualified ribs and tubes automatically. This enables the CAE engineer to perform a trial-and-error analysis and the modification of the CAD design during the CAE analysis stage.

Keywords: DFM analysis, design modification, feature recognition, thin-wall part, design guideline

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1 INTRODUCTION

Mold flow analysis has been widely used in injection molding to help with product design, mold design, and process improvement. CAD design may not follow the requirements of mold flow analysis, or it must be modified after analysis. In current practice, mold flow analysis and CAD modeling are often carried out separately by different engineers. When CAD modification and CAE analysis is performed back and forth between different engineers, the entire process is often lengthy and error prone. Design for manufacturing (DFM) is a technique used to evaluate the

manufacturability of a design by analyzing the CAD model based on a set of design guidelines. In injection molding, various qualitative and quantitative design guides are generally available [1-4]. However, a designer may still produce a design that is un-producible or un-acceptable due to a lack of experience, unfamiliarity with design guides, or the complexity of the product. Therefore, the development of a tool that can check the feasibility of a CAD design and modify it for mouldability is helpful for product design.

Research on DFM analysis varies for different manufacturing processes, such as machined parts [5-8], sheet metal parts [9-12], die-cast parts [13-16], and injection parts [17-20]. The automatic manufacturability analysis of injection-molded and die-cast parts are studied simultaneously as both belong to the molding-type process [21, 22]. Feature-based manufacturing employs features to bridge the gap between design and downstream applications [23] and is the main issue addressed in DFM analysis. Typical features addressed in DFM analysis for injection or die-cast parts include thickness, boss, rib, draft angle, undercut, sharp corner, and fillet. The feature extractor is the most crucial subject in DFM analysis as it determines the kind of features that can be analyzed.

In relation to DFM analysis, Yang et al. [24] investigated the rib design in the gas-assisted injection molding process where an experimental study was performed to investigate the effects of rib geometry, including aspect ratio and fillet, on mouldability and rigidity. Carter et al. [25] investigated and quantified the effects of various topological and parametric designs on the structural performance of five types of plastic bosses. Jeong [26] studied the optimized design of reinforcing ribs within an objective limit in ABS resin and a high glossy surface, where the design variables included a variation of thickness, height, and draft angles. James [20] proposed a DFM advisory system for the feature design of plastic injection parts, where a feature extraction algorithm was developed to recognize holes, bosses, ribs, drafts, undercuts, and radius. Madan et al. [13] proposed an automated system for the manufacturability analysis of die-cast parts. A knowledge base consisting of die-casting process knowledge and rules was employed to present manufacturability advice to the designer.

Ristic et al. [14] presented the concept of a system for the manufacturability analysis of die-cast parts. A method to create knowledge on the basis of recommendations and restrictions for the design of die-cast parts was described. An advisory system providing the upgrade of the design and the concurrent engineering environment was also addressed. Kumar et al. [15] presented an automated system for the DFM analysis of die-cast parts. It included a knowledge base of DFM guidelines, die-casting feature extraction from the parts CAD model, and an automated system for DFM analysis and model updating. Specifically, it extracts various die-casting features such as wall thickness, boss features, rib features, draft features, sharp corners, and edges to solve the manufacturability problems. Chan et al. [18] presented a basic structure for an interactive knowledge-based injection mold design system. It covered both the mold design process and mold knowledge management and included many developed interactive tools within a commercial CAD system.

In relation to a feature extractor, Lockett et al. [27] presented a feature recognition approach for thin-walled injection molded and cast products by abstracting the mid-surface of the parts geometry. Mok et al. [28] proposed a hybrid approach for the feature recognition of injection molded parts, where features of plastic products were classified into three hierarchical levels; primitive features, complex features, and high-level complex features. Deng et al. [17] described a feature-based CAD-CAE integration model for injection-molded product design, where each feature was specified by its attributes (both geometric and non-geometric information) and behaviors (e.g. feature creation, manipulation, decomposition). Specified information from the design process was also used to activate relevant CAE analyses. Bidkar et al. [22] proposed a mathematical framework to automatically evaluate the manufacturability of injection and die-cast parts. A novel feature recognition based on decomposing the part into elemental cubes was proposed. The algorithms for the recognition of parting surfaces, parting lines, undercuts, holes, bosses, and molding direction were primarily addressed.

The purpose of this study is to develop a DFM analysis and design modification method for ribs and tubes on thin-wall plastic injection parts. The fundamental issue of this study is presenting a framework for feature recognition of thin-wall parts. A DFM analysis method is then developed to evaluate the feasibility of the dimensions related to several features, such as fillets, ribs, and tubes, based on a set of rules from various design guidelines. A design modification method is finally proposed to modify unqualified rib and tube dimensions automatically. The main contribution of this study is to integrate feature recognition, DFM analysis, and feature modification so that design analysis and modification can be implemented simultaneously. This would enable engineers to perform a trial-and-error analysis and modification of CAD designs during the CAE analysis stage.

2 OVERVIEW OF THE PROPOSED METHOD

A thin-wall plastic part can be separated into inside and outside, where the faces that are invisible once two parts are assembled are on the inside and the residual faces are on the outside. Figure 1 depicts the terms used in this study for thin-wall parts. The faces on the outside are known as outer faces and those on the inside are called inner faces. The inner faces are divided into transition, wall, bottom, and protrusion faces. Transition faces connect inner and outer faces simultaneously. Bottom and wall faces are those on the inner bottom and side of the model, respectively. Transition, bottom, and all wall faces are called auxiliary faces as they are used to help with the recognition of protrusion faces. In a CAD model, both protrusion and depression features may exist simultaneously. However, depression features such as holes usually exist alone and can be recognized individually. On the other hand, protrusion features such as ribs, bosses, tubes, and columns are more complex in shape and composition. Therefore, we emphasize the recognition of protrusion features hereafter.

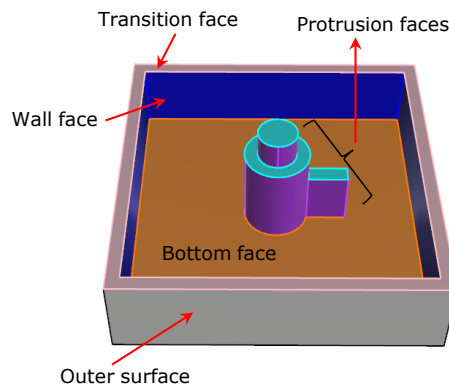


Figure 1: Face compositions on a thin-wall part.

Figure 2 depicts the flowchart of the proposed DFM analysis and modification system, which is predominantly divided into two parts: feature recognition and design analysis and modification. In feature recognition, preliminary functions are implemented to prepare the data for protrusion recognition. They mainly provide edge and face databases and fillet and hole data [29]. Edge and face databases record the attributed adjacency of edges and faces, respectively. Fillet data records the type of a fillet and its adjacent faces while hole data records the compositing faces of a hole and its hole type. Fillets and holes must be respectively identified first as they are used at the recognition of auxiliary faces. The proposed protrusion recognition algorithm is not only for the recognition of ribs and tubes, but also other protrusion features. However, we only focus on the recognition of ribs and tubes in this study.

In design analysis and modification, the data required for DFM analysis are firstly computed. The data recorded in feature recognition are the face compositions of each feature only. The topological relationship of edges and faces with respect to each feature should be computed, which can be used for evaluating the feature dimensions in DFM analysis. The feature data evaluated in this study include fillets, ribs and tubes. Secondly, rib and tube dimensions that are addressed in design guidelines [1-3] are computed. A feature may or may not be rounded at its feature edge. Both situations must be considered in dimensional evaluation. Erroneous dimensions that do not follow design guidelines are highlighted and recorded. Finally, design modification of ribs and tubes is performed. An automatic feature modification algorithm is proposed to modify all un-qualified ribs or tubes simultaneously with respect to specific feature dimension checked.

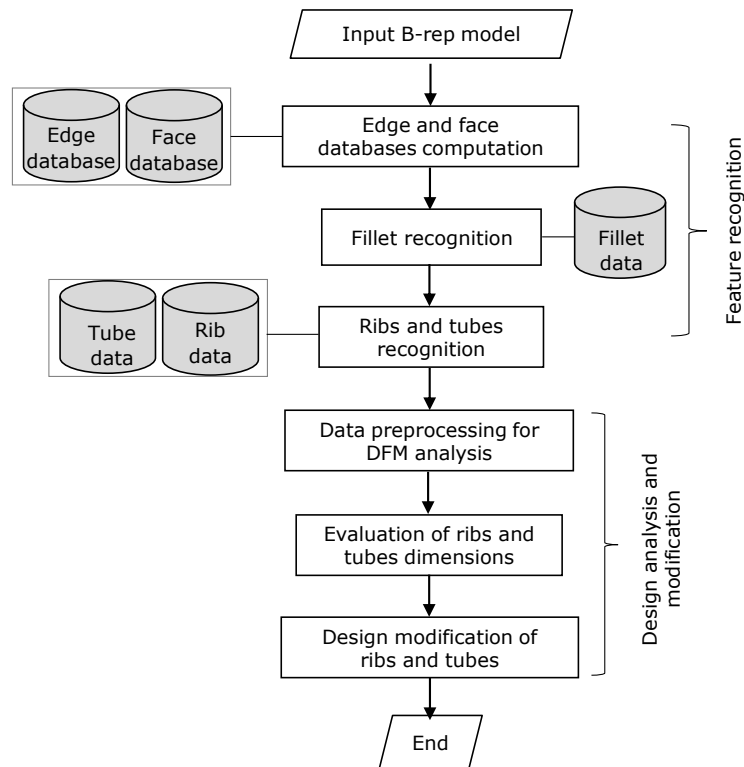


Figure 2: The proposed DFM analysis and design modification algorithm.

3 FEATURE RECOGNITION METHOD

Protrusion features include rib, tube, column, polygon block, and irregular extrusions. Boss is another protrusion feature that is commonly mentioned in literature. However, a boss may be considered as the combination of a tube and ribs, and hence is neglected herein. In the proposed feature recognition method, auxiliary faces on a thin-shell CAD model are recognized first. They can serve as the boundary constraint for the search of each group of protrusion faces. The overflow of erroneous faces on a group can thus be reduced substantially. Protrusion recognition is mainly divided into four steps. Firstly, an algorithm is employed to recognize the inner and outer faces of a thin-wall part. Secondly, auxiliary faces, including transition, wall, and bottom faces, are recognized. Thirdly, protrusion faces that are adjacent to each other are evaluated and grouped. Finally, the feature type of each group of protrusion faces is classified and associated data is

outputted. A detailed description of the algorithms used for the first three steps is given in [30]. We focus on the recognition of tubes and ribs from a set of protrusion faces that link together to form a complex structure.

A typical tube and rib structure on a CAD model is shown in Figure 3(a). A tube may stand alone or is supported by several ribs. A rib that stands alone is called a single rib. A series of ribs that connect together is called a rib structure. A rib structure is composed of two kinds of patterns: a rib segment and a transition region. A rib segment is a segment with a pair of matching faces that are symmetric or almost symmetric, whereas a transition region is essentially the junction of rib segments. A single rib is considered a rib segment. There are basically two types of ribs, planar and curved ribs, where the matching faces of the former and latter are planes and surfaces, respectively.

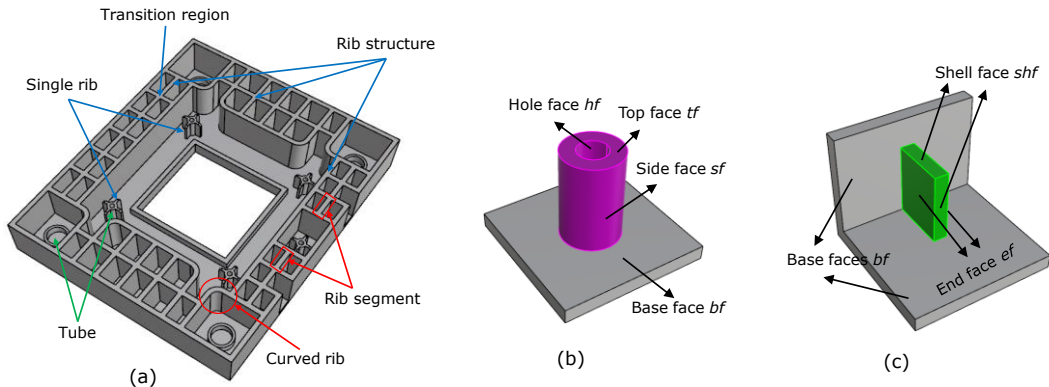


Figure 3: Basic structure of tubes and ribs: (a) tube and rib types, (b) face composition of a rib, and (c) face composition of a tube.

The basic structure of a tube is shown in Figure 3(b), which is composed of four kinds of faces: top face (tf), side face (sf), base face (bf) and hole face (hf). The sf and hf are cylindrical faces, with both central axes parallel to each other. There are three main steps to recognize a tube from a group of protrusion faces. Firstly, search for holes that are located on the protrusion faces. Secondly, start with one of the holes, say h_i , search for cylindrical faces adjacent to the base face of h_i . Thirdly, compare the central axis of each cylindrical face with h_i . If it is located on the inside of h_i and also perpendicular to the base face of h_i , then a tube exists and its composition faces can be evaluated. The base face of the hole is the tf , the cylindrical face is the sf , and the hole face is the hf of the tube. Also, the bf of the tube can be evaluated by using the sf . This procedure is performed repeatedly for all holes on the same group of protrusion faces to yield all tubes. It is noted that a tube may contain multiple side faces that are separated by ribs. The above-mentioned procedure can deal with such a situation. Figure 4 shows the intermediate results for the evaluation of a tube for an example. Figure 4(a) depicts a group of protrusion faces with four holes inside. Figure 4(b) indicates one of the holes, say h_i , addressed. Figure 4(c) shows the cylindrical faces adjacent to the base face of h_i . Figure 4(d) shows the composition faces of the tube with respect to h_i . As the top face is a virtual face that covers multiple features, it could be necessary to slice this face and yield the customized edges and faces for the top face of the tube, as shown in Figure 4(e).

The basic structure of a rib segment is shown in Figure 3(c), which is composed of three kinds of faces: end face (ef), shell face (shf) and base face (bf). The two end faces are perfectly or nearly parallel to each other. The shell faces are on the top and side of the rib and are between two end faces. The base face is a face where the rib is resided. Multiple base faces usually exist, including wall and bottom faces. As ribs are primarily linked together and form a complex structure, the initial rib data are obtained by using a rib recognition algorithm [31]. Tubes are

regarded as curved ribs in [31] as they are not separately considered. Figure 5(a) depicts the result of rib recognition for a CAD model, where planar and curved ribs are colored in green and purple, respectively. Curved ribs that belong to tubes and columns should be separated in this study.

The *shf* of a rib is commonly a virtual face that serves as the top face of multiple features, including tubes and columns. Therefore, for a group of protrusion faces with initial rib data obtained in [31], its *shf* can be used to check the existing of adjacent protrusion features. Consider that the *shf* to be checked is f_i , Search for all faces neighboring to f_i . If a neighboring face is neither a face belonging to a rib nor a tube, then it should be recorded because it belongs to other protrusion features. Figures 5(b) and (c) show the results of two cases after the implementation of tube and rib recognition algorithms. In Figure 5(b), the left plot indicates the original group of protrusion faces (red) for case 1. The middle plot indicates the rib faces (green) and tube faces (yellow) after the implementation of both recognition algorithms. Finally, the right plot indicates that no more processing is needed as all faces have been recognized. In Figure 5(c), the left plot indicates the original group of protrusion faces (red) for case 2. The middle plot indicates the rib faces (green) after the implementation of both recognition algorithms. It is noted that two cylindrical faces (red) are still regarded unknown as there is no tube in this case. Therefore, the right plot indicates that the faces colored in red, including the *shf* of the rib, are remained unrecognized after the implementation of both algorithms.

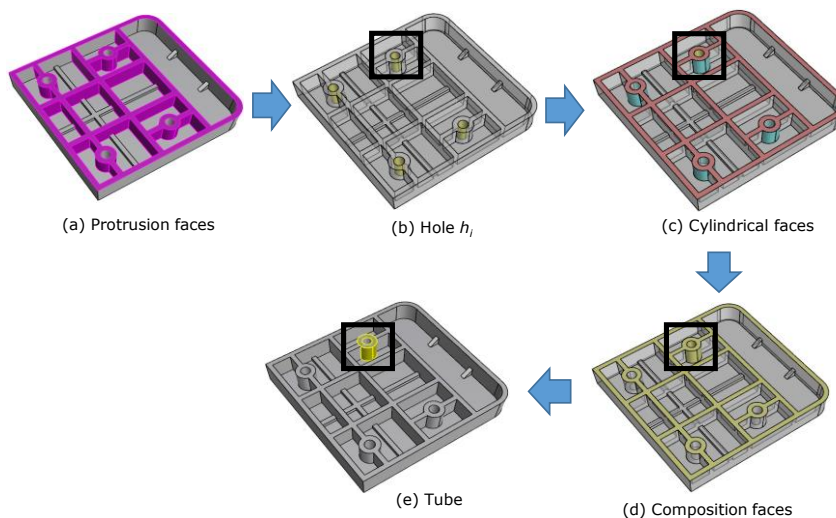


Figure 4: Recognition and separation of a tube: (a) protrusion faces, (b) hole h_i investigated, (c) all cylindrical faces adjacent to the base face of h_i , (d) composition faces of a tube recognized, and (e) calculate customized edges and faces.

The data structure of features for DFM Analysis must be developed. In feature recognition, the data recorded for a feature primarily only include its face compositions. However, in DFM analysis, the topological data of the edges and faces of a feature is required to evaluate the parameters used in the design guidelines. Therefore, it is necessary to establish a complete data structure for each feature. Ribs and tubes are primarily investigated in this study and sharp corners are usually rounded with fillets. Consequently, the data structure of fillets, ribs, and tubes used for DFM analysis must be developed. Figure 6 depicts the data structure of fillets for DFM analysis, where Figure 6(a) shows the definition of terms and Figure 6(b) shows the entity composition on the data structure. Similarly, Figures 7 and 8 depict the data structure of tubes and ribs, respectively, for DFM analysis.

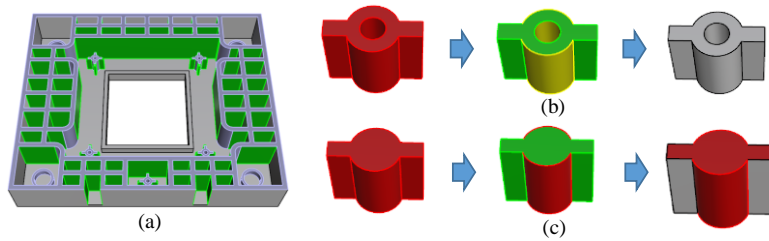


Figure 5: Initial rib data and the results after the implementation of tube and rib recognition: planar and curved ribs recognized, (b) case 1: adjacency of a tube and a tube, and (c) case 2: adjacency of a rib and a column.

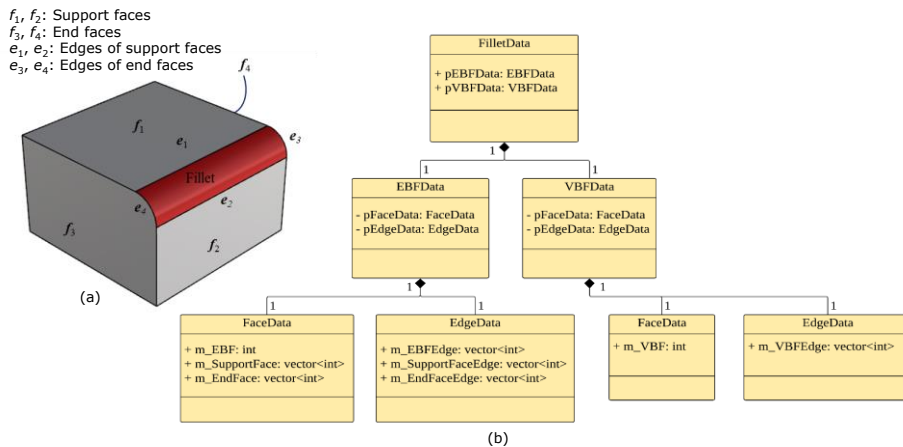


Figure 6: Data structure of fillets for DFM analysis: (a) definition of terms, and (b) entity composition on the data structure.

4 DESIGN FOR MANUFACTURABILITY (DFM) ANALYSIS

Rib and tube dimensions for DFM analysis are depicted in Figures 9(a) and (b), respectively. Rib dimensions include part thickness (t), rib thickness (T_r), rib height (H_r), draft angle (θ_{dra}), rib space (d_r), and base radius (R_r). Tube dimensions include tube thickness (T_t), tube height (H_t), draft angle of tube (θ_{dra_o}), draft angle of hole (θ_{dra_i}), outer diameter (D_o), inner diameter (D_i), and base radius (R_t). Tables 1(a) and (b) list effective ranges of rib and tube dimensions as per design guidelines, respectively. The specific range of values allowed for each dimension may vary in different guidelines, but the types of dimensions to be checked are identical.

A. Rib Dimensions Computation

The rib dimensions computed in this study include part thickness (t), rib thickness (T_r), rib height (H_r), draft angle (θ_{dra}), base radius (R_r), and rib space (d_r).

- (a) **Part thickness (t):** The thickness of a thin-wall part may not be constant. Therefore, the part thickness near a rib should be evaluated. The part thickness of a rib is defined as the part thickness near its base face. Therefore, the face that has the minimum distance along the surface normal to the base face is chosen, and this distance is regarded as the part thickness of the rib. Part thickness for a tube can also be evaluated in a similar way.
- (b) **Rib thickness (T_r):** As depicted in Figure 10(a), for the shortest edge on the bottom, namely e_1 , evaluate the middle point, P_m . Compute a measuring direction; $V_m = V_t \times V_z$, where V_t is the directional vector of e_1 and V_z is the mold opening direction. V_m intersects

another end face to yield a point, P_i . The distance of P_m and P_i is regarded as the rib thickness, T_r . If fillets exist on the bottom, then P_m and P_i are evaluated as shown in Figure 10(b).

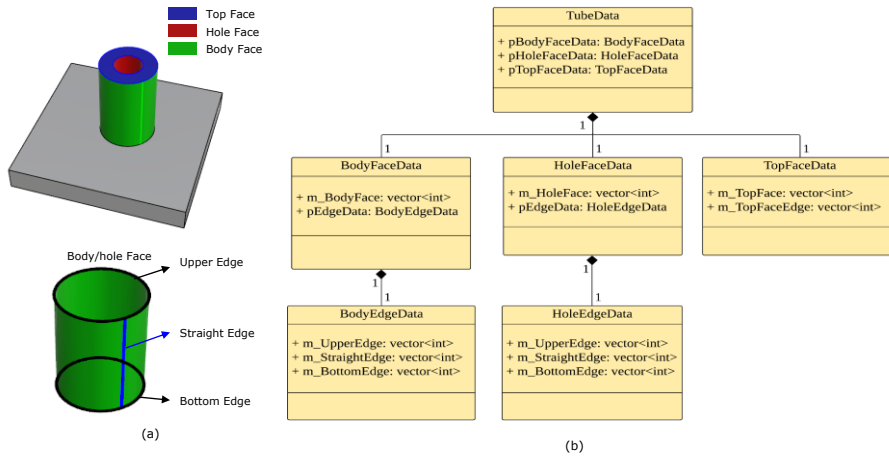


Figure 7: Data structure of tubes for DFM analysis: (a) definition of terms, and (b) entity composition on the data structure.

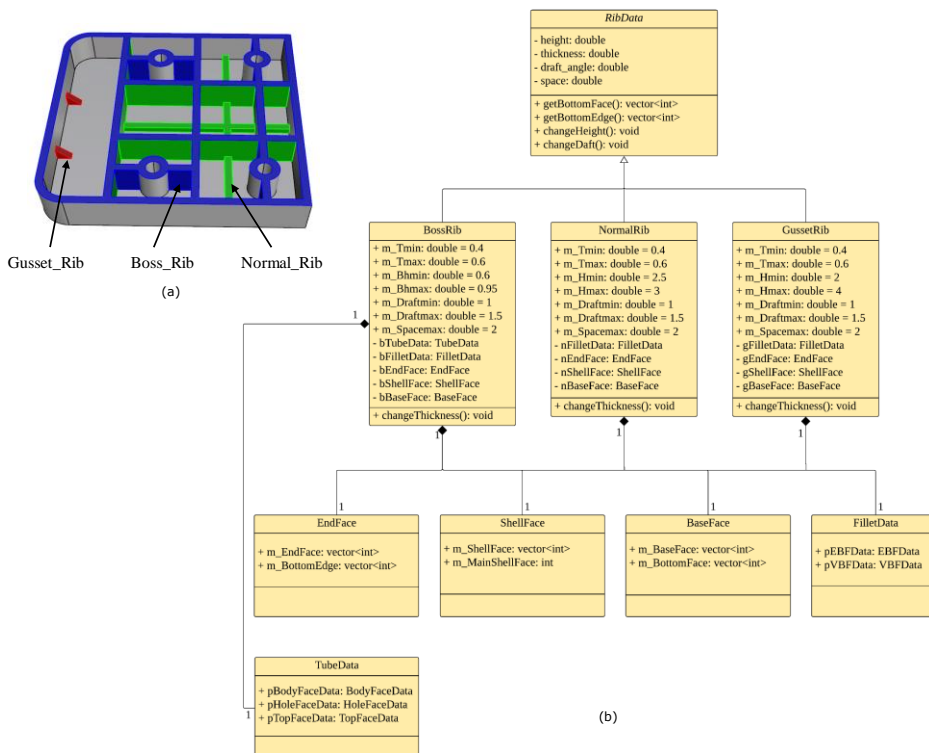


Figure 8: Data structure of ribs for DFM analysis: (a) definition of terms, and (b) entity composition on the data structure.

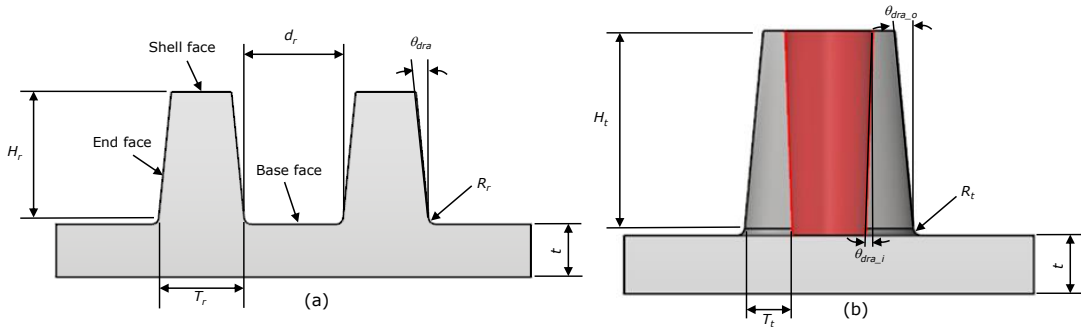


Figure 9: Parameters used in design guidelines: (a) rib, and (b) tube.

Parameter	Effective range		
	Normal rib	Boss rib	Gusset rib
Thickness (T_r)	$t*0.4 < T_r < t*0.6$		
Height (H_r)	$t*2.5 < H_r < t*3$	$0.6*H_t < H_r < 0.7*H_t$	$t*2 < H_r < t*4$
Draft angle (θ_{dra})	$1^\circ < \theta_{dra} < 1.5^\circ$		
Space (d_r)	$d_r > t*2$		
Base radius (R_r)	$t*0.25 < R_r < t*0.4$		

(a)

Parameter	Effective range
Thickness (T_t)	$T_t \approx t*0.6$
Height (H_t)	$H_t < D_{out}*3$
Outer draft angle (θ_{dra_o})	$\theta_{dra_o} \geq 0.5^\circ$
Inner draft angle (θ_{dra_i})	$\theta_{dra_i} \geq 0.25^\circ$
Space (d_t)	$d_t > t*2$
Base radius (R_t)	$t*0.25 < R_t < t*0.5$

(b)

Table 1: Effective range of rib and tube dimensions: (a) rib, and (b) tube.

- (c) **Rib height (H_r):** Rib height is defined as the distance between the shell and base faces. As depicted in Figure 10(c), the highest point, P_h , on the shell face is evaluated. It is projected onto the base face along the mold opening direction, V_z , to yield the projected point, P_l . The distance of both points denotes the maximum rib height.
- (d) **Draft angle (θ_{dra}):** The draft angle of each end face of a rib is the angle between its surface normal and the mold opening direction, V_z .
- (e) **Base radius (R_r):** The radius of a fillet between an end face and the base face. This can be obtained from the fillet data.
- (f) **Rib space (d_r):** The rib space is regarded as the distance between two neighboring ribs. It is evaluated by generating a measuring direction, V_m , on a bottom edge of a rib, and evaluating the points of intersection with all other ribs. The rib with the minimum distance is considered as the neighboring rib, and the corresponding distance is the rib space.

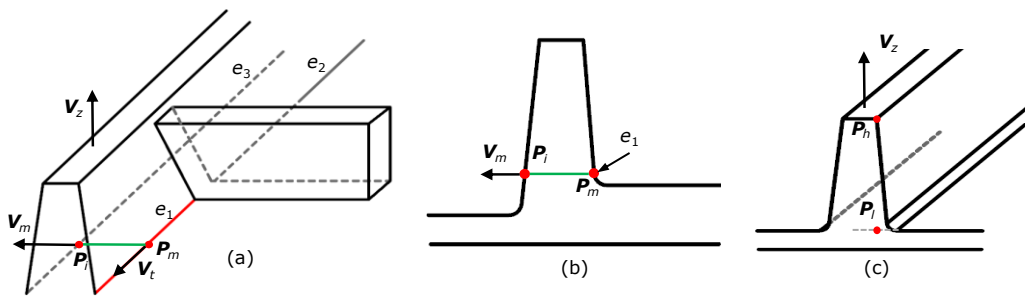


Figure 10: Evaluation of rib thickness and height: (a) rib width without fillets on the bottom, (b) rib thickness with fillets on the bottom, and (c) rib height.

B. Tube Dimensions Computation

The tube dimensions computed in this study include tube thickness (T_t), tube height (H_t), outer and inner draft angles (θ_{dra_o} and θ_{dra_i}), and tube space (d_t).

- Tube thickness (T_t):** Tube thickness is the difference between the outer radius and inner radius. Both radii can be obtained from the edges on the top face of the tube.
- Tube height (H_t):** Each tube has two centers on its inner face or its outer face. The distance between these two centers represent the tube height.
- Outer and inner draft angles (θ_{dra_o} and θ_{dra_i}):** The outer draft angle is the draft angle of the outer face, whereas the inner draft angle is the draft angle of the inner face. Both angles can be obtained with a method similar to that used for the rib draft angle.
- Tube base radius (R_t):** The tube base radius is obtained with a method similar to that used for the rib base radius.
- Tube space (d_t):** Tube space is evaluated with a method similar to that used for the rib space.

After the analysis, unqualified ribs and tubes are colored differently in accordance with the error type. A layer on Rhino (a CAD platform used in this study) was created to display multiple types of errors. Whenever an error occurs on a rib, a parent layer corresponding to this rib is created. A child layer is created when multiple errors for the same rib occurs. A text file was also generated to display all error types in detail. Figure 11 depicts the layer design on Rhino and the color display of faces with respect to unqualified rib and tube dimensions, where unqualified height, draft angle, and thickness are colored in green, yellow, and red, respectively.

5 DESIGN MODIFICATION OF RIBS AND TUBES

The design modification of a rib was achieved by moving a point, edge, or face of the B-rep model with respect to the rib (Figure12). As the proposed system was implemented on the Rhino platform, the function `ON_TransformBrepComponents()` on Rhino SDK [32] was employed to achieve the task. Two parameters are specified on this function: (1) the moving vector, \mathbf{V}_m , required to move an object from points A to B, and (2) the object, O_m , to be moved which can be a point, edge, or face. By specifying different moving objects, O_m , we can achieve the modification of rib width, height, draft angle, and position. Possible modifications are described below:

- Modification of rib thickness (without fillets):** The moving objects, O_m , are both end faces of the rib. The moving vector $\mathbf{V}_m = \pm d(\mathbf{V}_z \times \mathbf{V}_e)$, where d is the moving distance, \mathbf{V}_z is the mold opening direction, and \mathbf{V}_e is the directional vector of an edge on the bottom. The rib becomes thicker if the positive sign is selected and thinner if the negative sign is selected.
- Modification of rib thickness (with fillets):** The moving vector, \mathbf{V}_m , is the same as (1), but the moving objects, O_m , should include both end faces and fillets that connect to both end faces.

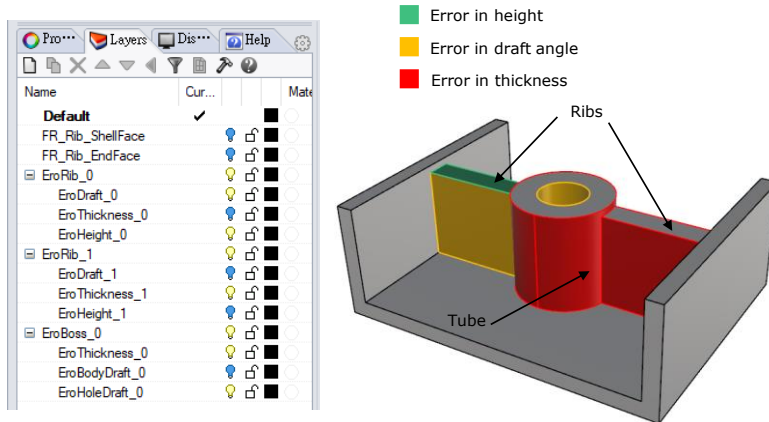


Figure 11: Display of unqualified ribs and tubes on Rhino after DFM analysis.

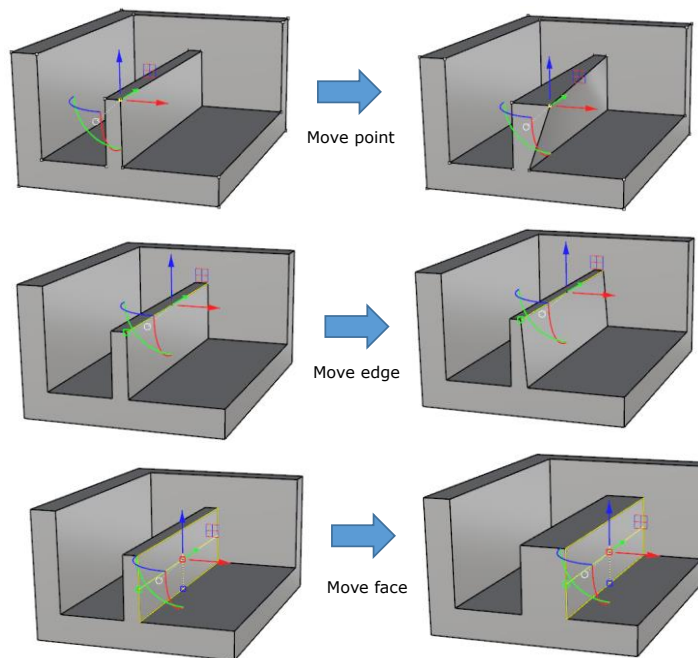


Figure 12: Design modification of a rib through the moving of a point, edge, or face.

- (3) Modification of rib height: The moving objects, O_m , are shell faces. The moving vector, $\mathbf{V}_m = +/-d\mathbf{V}_z$, where the rib becomes higher if the positive sign is selected and lower if the negative sign is selected.
- (4) Modification of draft angle: The moving objects, O_m , are the common edges of shell and end faces. The moving vector, $\mathbf{V}_m = +/-d_\theta\mathbf{V}_E$, where \mathbf{V}_E is the surface normal of one end face and d_θ is the distance with respect to the desired draft angle.
- (5) Translation of rib: The moving objects, O_m , are: (1) when the shell face is not a virtual face, O_m includes both end faces and the shell face; (2) when the shell face is a virtual face, O_m are only both end faces. The moving vector, $\mathbf{V}_m = +/-d\mathbf{V}_E$, where \mathbf{V}_E is the surface normal of one end face and d is the moving distance. Both end faces should be moved in the same direction.

The design modification of a tube includes modifications of tube height, thickness, and draft angle. The algorithms are described below:

- (1) **Modification of tube height:** The algorithm is similar to that of the rib height, where the moving vector, \mathbf{V}_m , is the same as that of a rib and the moving object, O_m , is the top face of the tube.
- (2) **Modification of tube thickness:** The modification of tube thickness is achieved by employing a Boolean operation to change the solid model. This is implemented in four steps: (1) generate the first column with a diameter larger than that of the inner hole of the tube, (2) perform a Boolean union for the tube and the column to yield a solid tube, (3) generate a second column with a diameter that can yield the desired thickness, and (4) perform a Boolean difference for the tube and the column to yield the modified tube.
- (3) **Modification of inner draft angle (Figure 13(a)):** The Boolean operation is implemented to change the inner draft angle. This includes the following three steps: (1) generate a column with a diameter larger than that of the inner hole of the tube, (2) perform a Boolean union for the tube and the column to yield a solid tube, (3) generate a conic column with a slope that can yield the desired inner draft angle, and (4) perform a Boolean difference for the tube and the conic column to yield the modified tube.
- (4) **Modification of outer draft angle (Figure 13(b)):** The Boolean operation is also implemented to change the outer draft angle. This includes the following steps: (1) generate a conical surface with a slope that can yield the desired outer draft angle, and (2) perform a Boolean union for the conic surface and the tube to yield the modified tube.

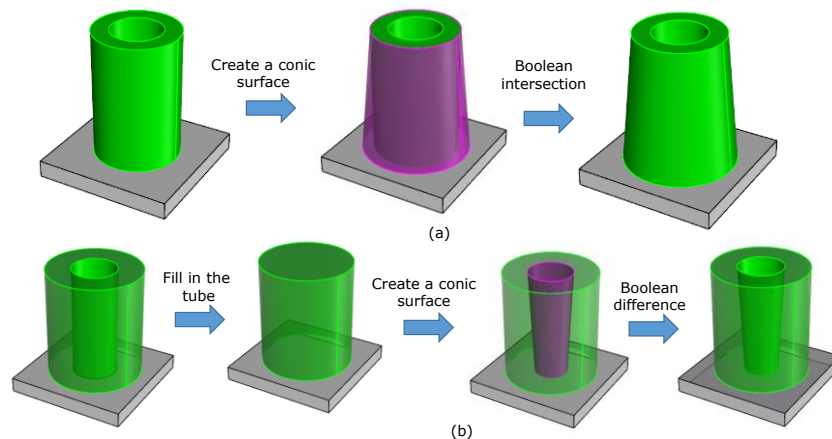


Figure 13: Design modification of a tube: (a) outer draft angle, and (b) inner draft angle.

6 RESULTS AND DISCUSSION

The proposed system is implemented in Rhino in an interactive way. Once the proposed system is executed, a CAD model must be selected. The feature recognition algorithm which can yield ribs, tubes, and fillets printed in different colors is then implemented. The next step is determining the mold opening direction, \mathbf{V}_z . The default direction is along the z direction, but the x or y direction can also be selected. The design guidelines implemented for ribs are rib width, draft angle, rib height, and rib space, and the design guidelines implemented for tubes are tube width, tube height, outer and inner draft angles. DFM analysis of all rib and tube dimensions is then implemented automatically and the corresponding faces of unqualified dimensions are indicated by different colors (as mentioned previously). Rib and tube dimensions can be modified manually or automatically. When manual modification is selected, the user can select the corresponding object (point, edge, or face) on a rib or tube to change its dimensions. Alternatively, when automatic modification is selected, dimensions that can be adjusted include rib width, rib draft angle, tube

thickness, and outer and inner draft angles. Once a dimension is selected, all ribs or tubes corresponding to this dimension are modified simultaneously.

The CAD model shown in Figure 14(a) is employed to demonstrate the feasibility of the proposed DFM analysis and modification system. The input data is a B-rep model of the part and the holes that connect to its inner and outer faces. The hole data can be accessed from the face database obtained in the preliminary functions. Figures 14(b) to (d) show the immediate results of the protrusion recognition. In Figure 14(b), the transition of inner and outer faces is the edges shared by the visible and invisible faces of a part when it is assembled with its counterpart. Figure 14(c) shows the result of the auxiliary faces recognition, where the auxiliary faces are recognized based on the inner faces obtained in Figure 14(b). It is noted that when the side wall of a part is higher than its internal features, the translation faces are distributed around the boundary of the inner surface. However, when some internal features are of the same height as the side wall, the translation faces can traverse across these features. Figure 14(d) shows the result of the protrusion feature classification, where only ribs and tubes exist in this example. The other three protrusion features are columns, polygon blocks, and irregular extrusions.

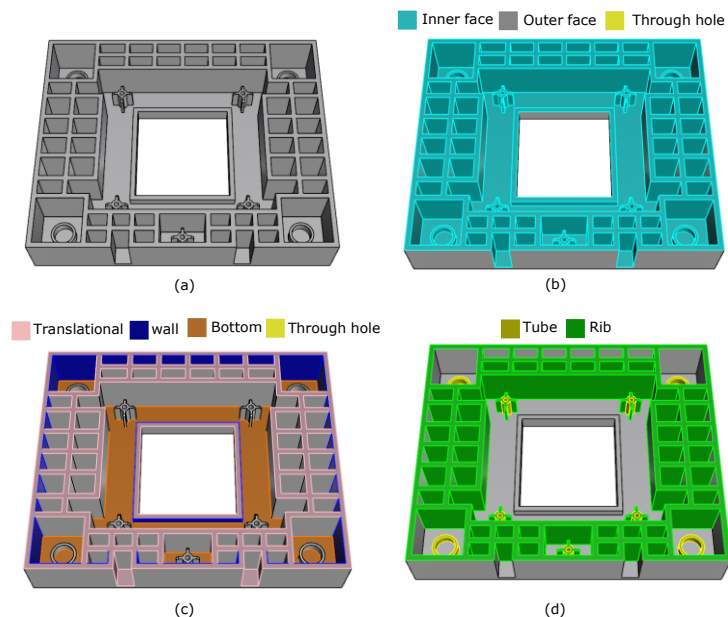


Figure 14: Results of protrusion recognition for one example: (a) input CAD model, (b) inner and outer faces recognition, (c) auxiliary faces recognition, and (d) classification of protrusion features.

The result of the DFM analysis and design modification is shown in Figure 15, where Figure 15(a) depicts the result of the DFM analysis and Figure 15(b) depicts the result of the automatic rib and tube modification. Erroneous dimensions found in this example include unqualified rib and tube thickness, and draft angles, as shown in Figure 15(a). Once the thickness is changed to 1.2 mm and the draft angle is changed to 1° . All ribs and tubes are modified automatically, as shown in Figure 15(b). Inappropriate thickness design may result in the presence of indentation of the plastic injection product. The main contribution of the proposed method was providing the DFM analysis for the rib and tube dimensions and an automatic modification method to change unqualified ribs and tubes automatically. In mold flow analysis, an original CAD design may not necessarily be satisfied in all features design, which means it is usually necessary to perform design modification and CAE analysis back and forth between design and CAE engineers. With the

proposed DFM analysis and modification system, an initial check of all dimensions can be performed before the CAE analysis is implemented, which can reduce the repetition of CAE analysis.

7 CONCLUSIONS

A DFM analysis and design modification system for plastic injection molding was developed in this study. It primarily involved a feature extractor to extract target features for analysis, a DFM analysis algorithm for the optimization of feature dimensions, and a design modification algorithm to modify unqualified feature dimensions automatically. The DFM analysis and design modification of rib and tube features were investigated in this study. The proposed feature extractor initially recognized auxiliary faces, including translation, wall and bottom faces, on the inner surface of a thin-wall part, and then grouped each set of adjacent protrusion faces. As the auxiliary faces can serve as the boundary constraints for the grouping of protrusion faces, it can reduce the excess of the faces in each group. Each set of protrusion faces could then be classified in sequence, where ribs and tubes were primarily investigated in this study. The proposed DFM analysis algorithm provided a data structure of rib and tube features for the evaluation of rib and tube dimensions. The optimization of feature dimensions included thickness, height, draft angle, base radius, and space for both ribs and tubes in accordance with various design guides. Finally, the design modification algorithm could modify all unqualified rib and tube dimensions automatically. This enables the CAE engineer to perform a trial-and-error analysis and the modification of the CAD design during the CAE analysis stage. In DFM analysis, radii, fillet, draft, undercut, and hole features are also commonly analyzed features. The proposed feature extractor and DFM analysis method can be expanded to cover these features though the design modification of each feature must be studied further.

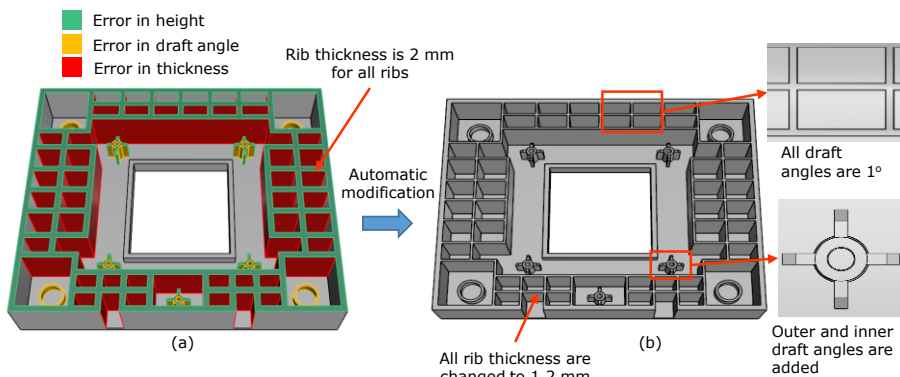


Figure 15: Automatic modification of unqualified rib and tube dimensions: (a) result of DFM analysis, and (b) result of automatic modification.

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