Feature-based Multi-resolution and Multi-abstraction Non-manifold Modeling System to Provide Integrated Environment for Design and Analysis of Injection Molding Products

Sang Hun Lee*
Kookmin University, Korea
shlee@kookmin.ac.kr

Kunwoo Lee
Seoul National University, Korea
kunwoo@snu.ac.kr

Kyu-Yeol Lee
Seoul National University, Korea
kylee@snu.ac.kr

Abstract

Current CAE systems for the injection molding process simulation and the structural analysis of plastic parts accept as geometric input solid models. However, abstract models composed of sheets and wireframes are still used in this area for more economic analyses. To obtain an adequate abstract model, it is often required to change the level of detail (LOD) and/or the level of abstraction (LOA) of the solid model. To meet this requirement, we developed a feature-based design system based on a non-manifold modeling kernel supporting the multi-resolution and multi-abstraction modeling capabilities. In this system, the geometric models for CAD and CAE systems are merged into a single part master model in the non-manifold topological (NMT) representation, and then, for a given LOD and LOA, the simplified solid or NMT analysis model is provided immediately. For a design change, the design and analysis models are modified simultaneously and maintained consistently. As a result, the system is able to provide a more integrated environment for the design and analysis of plastic injection molding parts.

Key words: injection molding product, integration of CAD and CAE, multi-resolution, level of detail, level of abstraction, feature, solid, non-manifold.

1. Introduction

3-D CAD systems based on feature-based solid modeling techniques have been widely used for product design. At the same time, engineering analysis using CAE systems has been an integral part of product design. In order to improve the product design process, it is crucial to integrate CAD and CAE closely, and ideally, seamlessly. Whether CAD and CAE applications can be closely integrated and automated depends upon the following factors: the scale, scope, and purpose of the CAE analysis; the nature and dimensionality of the CAD model; and the amount of detail required for the CAE application.

In the area of design and manufacturing of plastic injection molding parts, there have been various trials to develop a specialized CAD system for plastic part and mold design [12, 13, 21], and to develop a CAE system to simulate the injection molding process to find defects before the manufacturing stage [11, 14, 32]. The design and manufacturing process supported by the CAD and CAE systems can be illustrated in Figure 1. At the initial design stage, the CAD system dedicated to the plastic part design can be used to enhance the design productivity. The structural analysis and the molding process simulation using CAE systems verify the initial design result. The mechanical capabilities and defects of a plastic part are

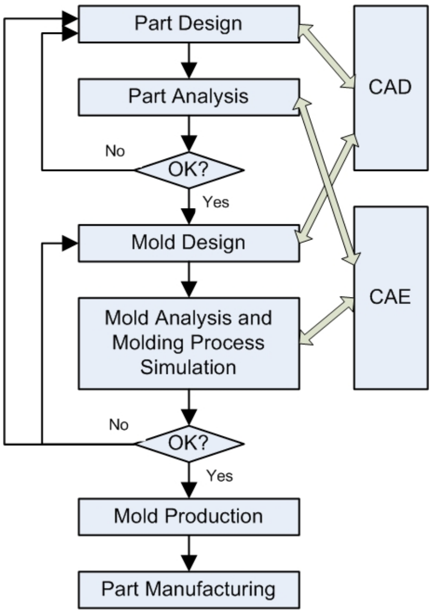

Figure 1. Design process using traditional CAD and CAE systems for plastic injection molding.

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* Corresponding author.

predicted through the analyses. If the simulation results do not satisfy the functional requirements, the design process is repeated by feeding back the simulation results. The design-analysis cycle is iterated until the functional requirements are satisfied.

Traditionally, the geometric models in design stage are solid models containing the feature representation such as ribs and bosses, whereas the models for analysis are abstracted NMT models composed of medial surfaces and axes as illustrated in Figure 2. As the solid-based CAD systems usually deal with solid models, the abstract model is created in the CAE system using its pre-processor. Therefore, the designer must create and maintain two types of geometric models for a part at the same time.

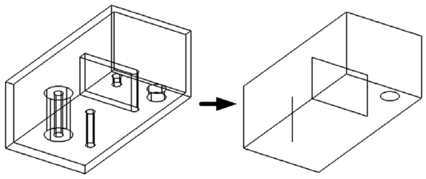


Figure 2. An example of abstract models for injection molding simulation and structural analysis.

To circumvent this problem, much effort recently has been done in two different ways: the one is to develop simulation methods that can accept solid models as geometric input, and the other is to automate transformation process from a solid into an abstract model. In the solid-based simulation approach, the detail removal that eliminates the insignificant features from the part model is still necessary for more efficient computation. In addition, although the solid-based approach can reduce the time for geometry preparation, the medial surface of the part is still useful because this type of approximation provide simulation results more rapidly without significant loss of accuracy comparing to the solid-based approach. However, the current automated transformation methods such as medial axis transformation (MAT) frequently require further modification of their results to meet the idealization rules for simulation. Therefore, if the idealized models for simulation can be readily provided in various LODs and LOAs from the design model, the cycle time for design-analysis iteration can be reduced dramatically.

To meet the requirements, we introduced the multi-resolution and multi-abstraction modeling techniques. In the proposed CAD system, various different geometric models for design and simulation are simultaneously created and merged into a NMT part master model, and for specific LODs and LOAs, analysis models in the solid or NMT representation are provided immediately from the master model. The proposed approach is expected to integrate the CAD and CAE systems more closely, and thus to realize the concurrent engineering methodology more readily.

The remainder of the paper is organized as follows. Section 2 surveys the related work on design, analysis, and design-analysis integration approaches including their component technologies. Section 3 describes how the system was designed. It includes the functional requirements, the adopted design-analysis integration approach, and the final system architecture. Section 4 describes the feature-based non-manifold (NMT) modeling for the creation and manipulation of part master models. Section 5 describes how analysis models at various LODs and LOAs are extracted from the master model using the multi-resolution and multi-abstraction modeling techniques. Conclusions are given in Section 6.

2. Related Work

Various CAD and CAE systems and their integration methods have been developed to support design and analysis for injection molding parts and their manufacturing. A wide range of key technologies are related with the development. Their literature survey is as follows.

2.1 Design

- **Injection molding product design systems:** Huh and Kim [12] developed a knowledge-based CAD system to support the initial design of injection molding products. This system contains two components: the one is an expert system for the optimal design of ribs and gates, the so-called RIBBER and GATEWAY, and the other is a three-dimensional geometric modeling system to represent design result in solid models. In order to develop the expert system, they gathered empirical equations and knowledge for design of ribs and bosses, and extracted the rules for the knowledge-based modules. Ishii et al. [13] proposed a system based on the design compatibility analysis methodology, in which product design is examined to determine how well it meets customers' requirements and the constraints on mold production and the injection molding process. Gadh et al. [8] emphasized the role of the systems based on experts' knowledge to judge the moldability for products as an alternative to numerical analysis systems. They also mention the representation and extraction of features for knowledge-based expert systems.

- **Feature-based design and feature recognition:** The feature-based design technique is implemented in most commercial CAD systems, and the feature recognition and extraction technology is still useful for automated abstraction of analysis models as details are usually suppressed in the unit of feature. For a comprehensive survey of feature technology, see [29].
- **Non-manifold topological (NMT) modeling**: Since the NMT model can represent any combination of wireframe, surface, solid, and cellular models in a unified data structure, it is convenient to represent NMT analysis model as well as solid design models in a single modeling environment. Several data structures have been proposed to represent NMT objects [16, 22]. Boolean operations on NMT models can be implemented based on the *merge & select* algorithm [7], which merges the input primitives into a single representation, and then selects the entities in the merged set that constitute the result of the Boolean operations. This method enables not only the efficient detection of feature interactions and efficient feature deletion [5] but also efficient extraction of geometric models at various levels of detail in multi-resolution solid modeling [15, 18, 19].

2.2 Analysis

- **Injection molding process simulation:** The injection molding process is composed of a series of filling, packing and cooling processes. There has been considerable research to predict defects and optimal injection molding conditions [11, 14, 32]. As a result, there have appeared various commercial CAE systems: Moldflow developed by Austin et al. [26], C-Mold developed by Wang et al. through the Cornell Injection Molding Program [32], and CAPA and MAPS-3D developed by VMTech [31]. These systems provide simulation capabilities for the entire molding cycle including filling, packing, and cooling stages. Recently, Moldflow provides a module that automatically converts CAD solid models into a finite-element mid-surface mesh model. In addition, using Dual Domain™ technology, users can work directly from 3D solid CAD models without the need to create or even view a finite element mesh, resulting in a significant decrease in model preparation time [26]. MAP-3D also provides full 3-D simulation capabilities [31]. However, detail removed models and mid-surface models are still useful for the reduction of computation time and storage without significant loss of accuracy.
- **Dimensional reduction**: Solid models are converted to appropriate lower-dimensional models, such as wireframes or sheets, using this technology. There have been attempts to use expert systems for selecting appropriate modeling abstractions [10], however these methods are not general and do not provide enough flexibility. The medial axis transform (MAT) [27], a technique closely related to Voronoi diagrams, is often used to produce results that are more generic. However, the result of the MAT is not appropriate as an analysis model, requiring an artificial adaptation process [1]. The mid-surface abstraction approach [28] has been suggested to overcome this problem. Recently, Belaziz et al. [3] attempted to use a feature-based tool based on a morphological analysis of the solid model, followed by simplification and idealization.
- **Detail removal**: Small geometric details present in the geometric model are ignored or suppressed by this technology. Expert systems have been introduced to extract form features from CAD models, and then selectively suppress the uninteresting features for the generation of analysis models [10]. Fourier transformation has also been introduced for geometric detail suppression by Y.G. Lee et al [24]. Clustering methods have also been presented that are suitable for the simplification of CAD models in preparation

for meshing [30]. Recently, Li and Liu [25] have developed a new metric system based on filleting to rate the LOD of boundary entities and they use this to decompose a solid into detail features.

2.3 Integration of Design and Analysis

- **Integration methodology:** Currently, there are three approaches to CAD and CAE integration: CAD-centric and CAE-centric, and CAD-CAE-integrated [9, 19]. In the CAD-centric process, the design is captured initially on a CAD system and an iterative design process requiring periodic analyses and design changes is used to improve or refine the design. In the CAE-centric process, engineering analyses are performed initially to define and refine a design concept using idealized analysis models before establishing the CAD product model. In the CAD-CAE integrated approach [19], different types of geometric models are simultaneously created for design and analysis for each feature modeling operation, and merged into a NMT part master model. For given LODs and LOAs, appropriate design and analysis models are extracted from the master model. The CAD-centric method has been widely adopted in the current design process. It is a challenge to apply the CAD-CAE integrated method to the injection molding part design.
- **Multi-resolution and multi-abstraction modeling**: The feature-based multi-resolution modeling of solids initially has been proposed by Choi et al [6]. In this approach, a conventional solid data structure is used as a topological framework for representing multi-resolution solid models. The lowest resolution model is made by uniting all of the additive features, and then higher resolution models are generated by applying subtractive features successively in the descending order of volumes. However, this approach is computationally expensive and does not allow an arbitrary rearrangement of additive or subtractive features. For efficient extraction of models at various LODs, Lee [23] introduced NMT models of a cellular structure for the multi-resolution representation. J.Y. Lee et al [15] applied this NMT approach to the progressive transmission of solid models through a network, for network-based collaborative design. Lee [18] introduced a measure of the effective volume of features to provide valid solids for an arbitrary rearrangement of features, regardless of feature type. Recently, Lee [19] proposed a new concept of multi-abstraction modelling in which the dimensionality of the features are varied at different levels of abstraction, and applied it to the CAD-CAE integration. This technique is adaptable to the integration of CAD and CAE systems for injection molding part design.

3. System Design

3.1 Functional Requirements

An integrated CAD/CAE system for the design of plastic injection molding parts should have the following functionality in order to support the feature and solid models for CAD systems as well as the abstract solid or NMT models for CAE systems. The representative CAE systems for injection molding product design are the molding process simulation packages and the FEM structural analysis system.

- **Design-with-feature capabilities:** In the design stage for a plastic part, the main shape is first determined, and then the size and location of sub-features, such as ribs and bosses, are determined to satisfy the given functional requirements of the part [12]. Thus, the three-dimensional CAD system must provide design-with-feature capabilities for plastic part design.
- **Non-manifold topological representation:** Not only solid models for design but also abstract models for analysis should be represented and provided efficiently. Shell meshes on the medial surface of a part need to be derived easily in order to get quick analysis results for initial part design. In order to generate shell meshes, at first, the main shape of a part is converted to a sheet model of mid-surface, and then sub-features are converted to sheets or wireframes depending on mesh size. Therefore, the NMT representation is essential to represent the analysis models composed of solids, sheets and

wireframes.

- **Multi-resolution and multi-abstraction modeling capabilities**: Current commercial analysis packages require CAD solid models or mid-surface models as geometric input. The multi-resolution and multi-abstraction modeling capabilities that provide various levels of abstracted models are useful at the initial design stage because they make it possible to reduce the computation time and storage without significant loss of accuracy.

3.2 System Architecture

To meet the requirements above, we introduced the CAD-CAE integration approach and implemented a feature-based NMT modeling system. The architecture of the system is shown in Figure 3. It consists of three main modules: a feature-based modeling module, a feature-based idealization module, and an NMT modeling kernel.

- **Feature-based modeling module:** This module manages the library and database of form features in their life cycle. This module creates, deletes, and modifies the form features in the part model, and maintains the hierarchical relationship among the features. This module sends messages to create or delete geometric models for features to the non-manifold geometric modeler.
- **Feature-based idealization module:** this module manages the idealization features, which are introduced to facilitate the idealization process, and performs the detail removal and dimension reduction tasks required to obtain application-dependent analysis models in solid or NMT representation. Multi-resolution and multi-abstraction modeling technology is implemented in this module.
- **NMT modeling kernel**: the kernel called NGM [22, 17] creates and manipulates all of the geometric models for the design and analysis stages. This kernel receives the messages from the feature-based modeling and idealization modules, and performs corresponding modeling operations. Especially, this kernel manages the merged-set models for parts, which are generated by merging all geometric models of the features for design and analysis. The sheet modeling and thickening functions for thin-walled parts are also provided by this kernel [20].

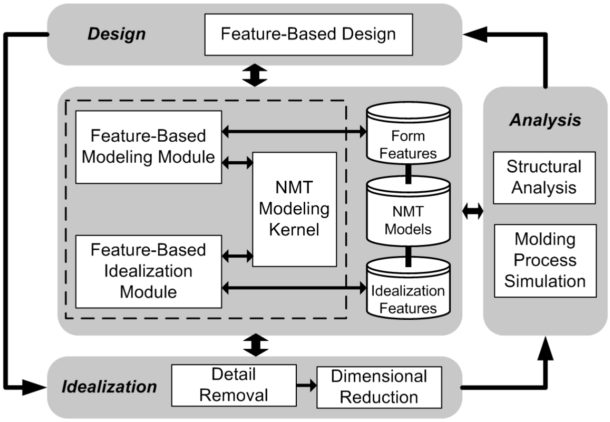


Figure 3. Design process in the CAD/CAE -integrated approach.

3.3 Design and Analysis Cycles

As illustrated in Figure 3, the iterative design process using the system is composed of three phases: design, idealization, and analysis.

(Phase 1) Design: the user conducts a part design using the feature-based modeling module. The user first creates the solid and mid-surface models for the main shape of the part, and then registers the solid and mid-surface models of the main part shape as a base feature. Next, the user creates sub-features sequentially. All geometric models of each sub-feature for design and analysis are merged into the part master model.

(Phase 2) Idealization: The feature-based idealization module is executed in this phase. If the user specifies the LOD, then the corresponding solid model is extracted from the master model. A series of solid models can be extracted at a sequence of LODs. These multi-resolution models can be used for analysis systems that require CAD solid models as geometric input. If the analysis system requires abstract models, then the multi-resolution models for various LODs and LOAs can be extracted from the master model. The analysis model is chosen from these multi-resolution models, and then transferred to the analysis system.

(Phase 3) Analysis: Various analyses such as structural analysis and molding process simulation are conducted in this phase. If the analysis results are not satisfactory, the user goes to the design or the analysis stage. This design-analysis cycle is iterated until the analysis results are satisfactory.

The first two phases are described in more detail in the following sections.

4. Feature-Based Design

4.1 Feature Creation and Deletion

In the design phase, the part master models are created or modified using the feature-based NMT modeling system. In the part modeling process the base feature for the main shape of the part is created first and then adequate sub-features are implanted sequentially. If necessary, the features can be removed using the feature deletion function.

- **Base feature creation: T**he user creates a solid model and an abstract model for the main shape of the part using the geometric modeling capabilities in the non-manifold geometric modeling system. Since the main shape is a thin-walled solid object, the user can create a sheet model for the outer or the inner wall using the sheet modeling capabilities in NGM and then apply the sheet thickening function that transform a sheet into a solid with the given thickness [17, 20, 22]. The abstract model for the base feature may be obtained through the MAT function, which is not provided by the system. If offsetting the sheet model of the outer or the inner wall generates the main shape, this sheet can be used as the abstract model for the base feature with some modification such as offsetting by the half of the thickness. Simultaneously with the registration of the main shape, a new part model is generated, and performing the Boolean union operation between the solid and the abstract models in the system creates the merged-set model.
- **Sub-feature creation:** In order to create sub-features, the user selects the feature from the menu and inputs data requested by the system. Then the system creates an instance for the new feature class and fills the record with input data, and connects features in the graph. Then the system creates the solid and abstract models according to the shape variables, and merges these two models into the part master model that is a merged-set NMT model. At this point, in order to prevent discontinuities in analysis models, the abstract models for an additive sub-feature are extended and trimmed by the abstract models of the feature to be attached. As a result, the dimensions of the feature abstract models may differ from those of the feature solid model. Currently, a limited number of features, such as boss, rib, or hole, are implemented in our system. The feature library will be extended in the future.
- **Feature deletion:** When the user instructs the system to delete a feature, it removes all vertices, edges, faces and regions originating from the solid and abstract models of the specified feature, and then eliminates the feature from the feature graph considering the hierarchical relationship with other features. In this system, if a parent feature is deleted, the child features are also deleted. If a feature has multiple parents, it would be deleted when all the parents are deleted. After a feature is deleted, the entities suppressed by that feature are revealed in the part geometry. It is simple to recover the removed entities because the NMT part master model stores all the topological entities and their historical record created during design.

Figure 4 illustrates a feature tree that creates an example solid model shown in Figure 2 by

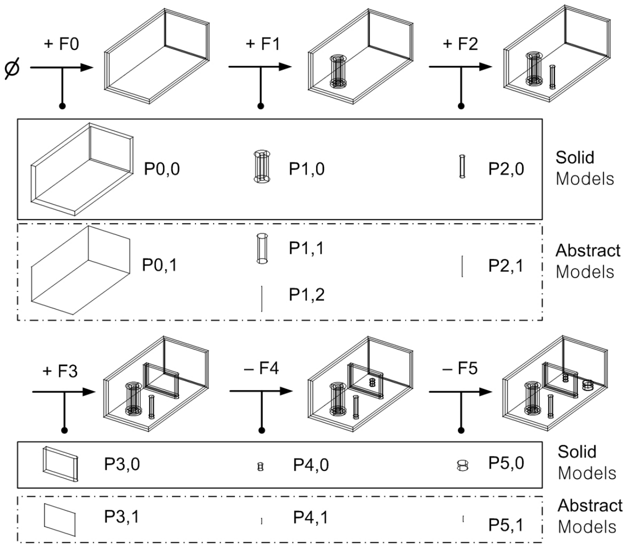


Figure 4. An example of feature-based solid modeling.

applying six features. Multiple geometric models are embedded into the master model in each feature modeling operation, unlike the conventional method in which only one model is embedded. One of these multiple models is a solid model for design, and the others are abstract models for analysis. If there is no abstraction required for analysis, the analysis model shares one solid model with the design model. The Boolean operation of a feature is determined by the type of the feature: If additive, the operation is union (+); If subtractive, the operation is difference (–).

4.2 Part Representation

The part model includes the feature and geometric data. Generally, form features are classified into three basic types: volume, transition, and pattern features. In this paper, form features are described using a volumetric representation and classified into additive and subtractive features. Transition features and feature patterns are converted to additive or subtractive volume features.

Features are connected to each other with a graph structure in which features have a parent-child relationship. The base feature for the main shape of the part is the starting node of the graph. The geometric model is represented with a merged-set model that is the result of a sequence of the Boolean operations among the features. The feature modeling history is recorded in the attributes of the part. The merged-set model is a non-manifold model that stores all topological entities of primitives for features, and the entities generated by intersection during the Boolean operations on implementation of features. The topological entities in the merged-set model all have records of their own birth. These records are used for feature deletion, feature intersection checking, abstract model extraction, etc.

The representation of the example part in Figure4 is described in Figure 5. Features are connected each other with a graph of the parent-child relationship. Each feature points to the solid and abstract models. Note that a feature can include two, or more, abstract models whose shapes can be wireframe, sheet, or solid. For instance, a boss can be abstracted into a wireframe or a cylindrical sheet. The abstract model for a depression feature such as a hole is just a wireframe. The type of abstract model depends on mesh size. In this system, all possible abstract models are stored in the part model, and one of them satisfying the condition is selected and extracted.

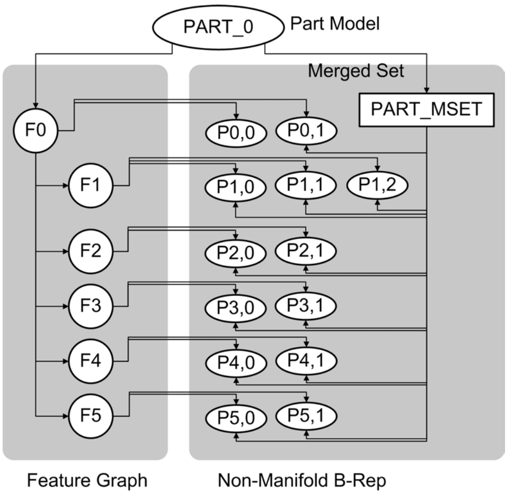


Figure 5. Example of part representation

5. Idealization

The idealization process to extract analysis models consists of detail removal and dimensional reduction stages. The multi-resolution modeling technique for feature-based solid models [18] is adopted for detail removal at various LODs. The multi-abstraction modeling technique for feature-based NMT models [19] is introduced for dimensional reduction at various LOAs.

In order to facilitate the implementation of the idealization process, the idealization feature is introduced as an extension of the multi-resolution feature [18]. A list of idealization features contains all necessary information for building multi-resolution and multi-abstraction models and for extracting LOD and LOA models from them. The attributes of the idealization feature are listed in Table 1, which is the initial state of the table before the feature rearrangement for the example model in Figure 4. Here, *D*, *A*, and *D/A* in the application domain column denote design, analysis, and design and analysis, respectively. In the multi-resolution modeling process, the related idealization features are extracted from this table, and then rearranged in the order of LOD. In the multi-abstraction modeling process, so does in the order of LOA. The stages of the idealization process are described in more detail in the following subsections.

Table 1. Initial idealization feature table for feature modeling in Figure 4

No	Feature Name	Creation Order	Bool	Appl. Domain	Primitive	Effective Zone	LOD/LOA Model
0	Base	0	+	D/A	$P_{0,0}$	$P_{0,0}$	
1	Base	0	+	A	$P_{0,1}$	$P_{0,1}$	
2	Boss1	1	+	D/A	$P_{1,0}$	$P_{1,0}$	
3	Boss1	1	+	A	$P_{1,1}$	$P_{1,1}$	
4	Boss1	1	+	A	$P_{1,2}$	$P_{1,2}$	
5	Boss2	2	+	D/A	$P_{2,0}$	$P_{2,0}$	
6	Boss2	2	+	A	$P_{2,1}$	$P_{2,1}$	
7	Rib	3	+	D/A	$P_{3,0}$	$P_{3,0}$	
8	Rib	3	+	A	$P_{3,1}$	$P_{3,1}$	
9	Hole1	4	–	D/A	$P_{4,0}$	$P_{4,0}$	
10	Hole1	4	–	A	$P_{4,1}$	$P_{4,1}$	
11	Hole2	5	–	D/A	$P_{5,0}$	$P_{5,0}$	
12	Hole2	5	–	A	$P_{5,1}$	$P_{5,1}$	

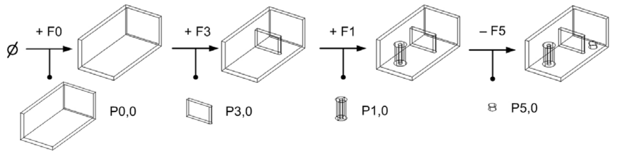
5.1 Detail Removal

Detail removal is the first stage of the part geometry idealization process. If the user wants to use some simplified solid models of the part to analyze the stress and strain distribution or to simulate the molding process, the suppression of the detailed features is essential. The process for detail removal consists of the following three steps. Let us explain the process using the example in Table 1. First, the idealization features whose application domain involves design, denoted D or D/A, are extracted from the table in Table 1. Next, the extracted idealization features are rearranged according to a given criterion of LOD such as the volume of the feature. The order of the features is changed to $F_0 \rightarrow F_3 \rightarrow F_1 \rightarrow F_5 \rightarrow F_2 \rightarrow F_4$. The effective primitives of features after the rearrangement are defined using Equation (4) in Ref. [18]. Finally, the user selects a simplified model at an appropriate LOD. The selected LOD model can be used for an analysis system that requires CAD solid models as geometric input. Table 2 and Figure 6 show four different LOD model definitions. If the user wants to reduce the dimensionality of the LOD model, he/she executes the dimensional reduction procedure successively.

Table 2. Reordered idealization features for the example solid model in Figure 4, according to the LOD criterion of the volume of feature.

No	Feature Name	Creation Order	Bool	Appl. Domain	Primitive	Effective Zone	LOD/LOA Model
0	Base	0	+	D/A	$P_{0,0}$	$P_{0,0}$	$P_{0,0}$
1	Rib	3	+	D/A	$P_{3,0}$	$P_{3,0}$	$P_{0,0} + P_{3,0}$
2	Boss1	1	+	D/A	$P_{1,0}$	$P_{1,0}$	$P_{0,0} + P_{3,0} + P_{1,0}$
3	Hole2	5	–	D/A	$P_{5,0}$	$P_{5,0}$	$P_{0,0} + P_{3,0} + P_{1,0} - P_{5,0}$

Figure 6. The LOD models according to the idealization feature table in Table 2.



5.2 Dimensional Reduction.

If the user wants to use some abstract analysis models of the part for structural analysis or molding process simulation, the dimensional reduction procedure is needed to be executed. The criteria of LOA are application-dependent. In the structural analysis, the aspect ratio is a good criterion to determine the abstraction level [1, 20]. Depending on the aspect ratio, a solid object may be abstracted to a beam element or a plate element. In the injection molding simulation, the ratio of the feature key dimension and the mesh size can be a criterion of LOA. For instance, if the diameter of a boss is less than the mesh size, it is abstracted to a wireframe model. Otherwise, it is abstracted to a sheet model. A hole is abstracted to a wireframe if its diameter is smaller than the mesh size. Eventually, these abstracted models are converted into FEM meshes such as linear triangles, cold/hot solid runners, cold/hot annular runners, and connectors. The linear triangle is a three-node shell mesh, and the others are all two-node beam meshes. Three node meshes are used to represent the main shape and ribs, and two node meshes are used to represent bosses, pins, runners, and gates.

In the multi-abstraction process, the system selects and marks the topological entities that contribute to building the abstract model for analysis. In the first step, the system copies the *0*-th to the selected *LOD*-th records of the idealization feature list to a new list. Next, for each given LOA, the system selects the appropriate abstract model for each idealization feature. The selection method is implemented in the class of each form feature. Using the selected feature abstract models, the Boolean sequence of each LOA model is redefined. To extract the idealized model on which a mesh is generated for analysis, the system copies the master model, selects the topological entities according to the Boolean sequence, and purges the unselected topological entities to get a clean NMT model. Finally, this model is transferred to CAE systems.

Let us follow the dimensional reduction process using the example in Table 1. Let us assume that *LOD=3* was selected and the LOAs of the feature primitives are ordered as $P_{0,0} = P_{5,0} = P_{2,0} = P_{3,0} \rightarrow P_{1,1} \rightarrow P_{3,1} \rightarrow P_{0,1} \rightarrow P_{1,2} \rightarrow P_{5,1}$. Figure 8 presents the idealization results of the example part model for varying LOD and LOA.

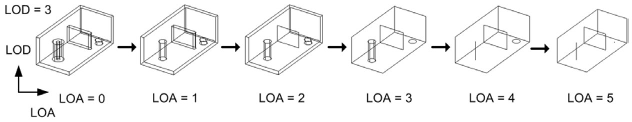


Figure 7. Abstract models of the example model at LOD=3.

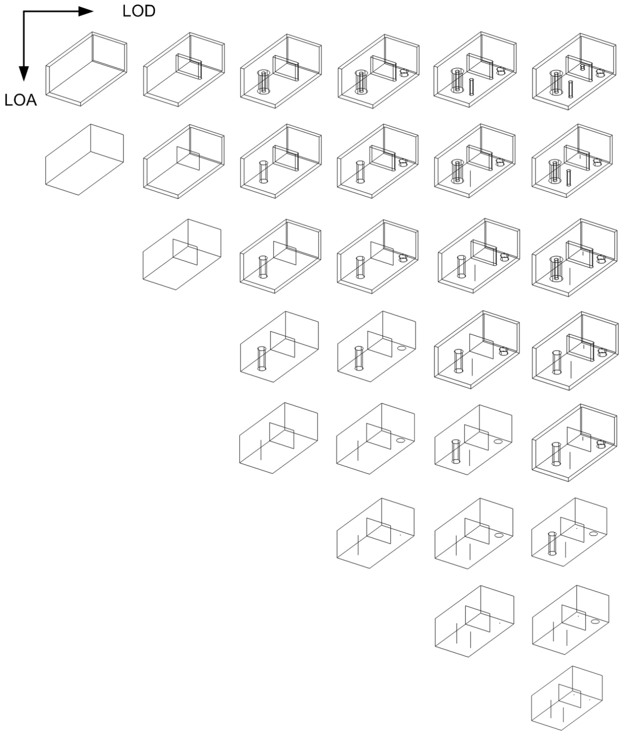


Figure 8. Idealized models for the example part

6. Conclusions

In this paper, we applied the multi-resolution and multi-abstraction modeling techniques to the integration of design and analysis of injection molding parts. In the proposed CAD system, various different geometric models for design and simulation are simultaneously created and merged into a NMT part master model, and for specific LODs and LOAs, analysis models in solid or NMT representation are provided immediately from the master model. In addition, using this information in the database, we easily implemented immediate feature deletion and the detection of feature interaction, which are difficult to implement with a solid modeler. Moreover, this system is implemented using the object-oriented programming technique, so the user can define and add a new feature into the feature library without changing the source code of the existing system. As a result, the proposed approach is expected to integrate the CAD and CAE systems more closely, and thus to realize the concurrent engineering methodology more readily.

However, to achieve more complete integration of the CAD/CAE system, the following tasks need to be conducted as future work: (1) integration of the MAT function to overcome the limitations of the design-by-feature method, (2) enlarging the feature library for the feeding system, such as gates and runners, (3) development of a more robust embedding method of abstract models, (4) evolving the system into a more intelligent one by adopting an expert system to evaluate the results of design and analysis.

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