Springer

Journal of Mechanical Science and Technology 23 (2009) 1331~1341

Journal of Mechanical Science and Technology

www.springerlink.com/content/1738-494x
DOI 10.1007/s12206-009-0407-3

Feature-based non-manifold modeling system to integrate design and analysis of injection molding products †

Sang Hun Lee*

School of Mechanical and Automotive Engineering, Kookmin University, Seoul, 136-702, Korea

(Manuscript Received December 30, 2008; Revised January 24, 2009; Accepted January 24, 2009)

Abstract

Current CAE systems used for both the simulation of the injection molding process and the structural analysis of plastic parts accept solid models as geometric input. However, abstract models composed of sheets and wireframes are still used by CAE systems to carry out more analyses more efficiently. Therefore, to obtain an adequate abstract model, designers often have to simplify and idealize a detailed model of a part to a specific level of detail and/or abstraction. For such a process, we developed a feature-based design system based on a non-manifold modeling kernel supporting feature-based multi-resolution and multi-abstraction modeling capabilities. In this system, the geometric models for the CAD and CAE systems are merged into a single master model in a non-manifold topological representation, and then, for a given level of detail and abstraction, a simplified solid or non-manifold model is extracted immediately for an analysis. For a design change, the design and analysis models are modified simultaneously. As a result, this feature-based design system is able to provide a more integrated environment for the design and analysis of plastic injection molding parts.

Keywords: Injection molding product; Integration of CAD and CAE; Multi-resolution; Level of detail; Level of abstraction; Feature; Solid; Non-manifold

---

1. Introduction

In the area of design and manufacturing of plastic injection molding parts, various trials have been carried out to develop a specialized CAD system that could be used to design of plastic parts and molds [1, 2, 3] and to develop a CAE system that could be used to simulate the injection molding process to find defects before the manufacturing stage [4-6]. The complete design process supported by the CAD and CAE systems is illustrated in Fig. 1. At the initial design stage, the CAD system dedicated to the design of the plastic part can be used to enhance design productivity. The structural analysis and the molding process simulation using the CAE system can validate the initial design. If the simulation results do not satisfy the functional requirements, the design process is repeated by feeding back the simulation results to the CAD system. The design-analysis/simulation cycle is iterated until the functional requirements are satisfied.

Traditionally, the geometric models used in the design stage are solid models including the feature information, whereas the models used in the analysis stage are abstract non-manifold topological (NMT) models composed of medial surfaces and axes, as illustrated in Fig. 2. The abstract NMT models are created in the CAE system using its pre-processor. Therefore, the designer must create and maintain two types of a geometric model of a part at the same time. Moreover, the process to convert a solid model into an abstract NMT model is very tedious and time-consuming.

† This paper was recommended for publication in revised form by Associate Editor Tae Hee Lee

*Corresponding author. Tel.: +82 2 910 4835, Fax.: +82 2 910 4839
E-mail address: shlee@kookmin.ac.kr

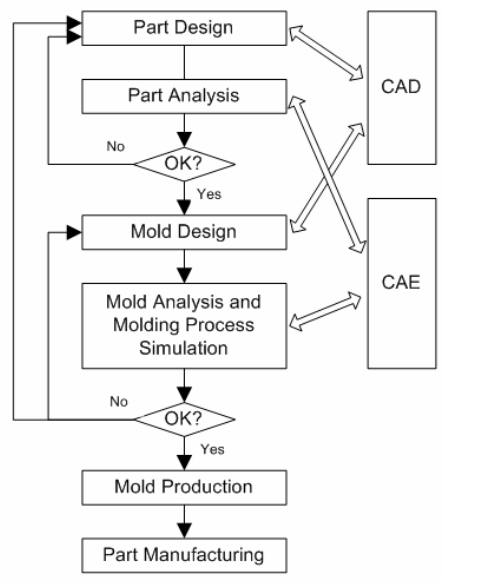

Fig. 1. Design and manufacturing process using traditional CAD and CAE systems for injection molding parts.

To solve this problem of having to create and maintain two types of models, two different approaches have been proposed recently. One is to develop a new simulation package that can accept solid models as geometric input, and the other is to develop a computer program that can automatically transform a solid model into an abstract model. In the solid-based simulation package, although the effort for transformation of a solid into an abstract model is eliminated, the computing time for the simulation increases dramatically. To shorten the time, it is still necessary to remove the insignificant features from a part model. In the automated transformation approach such as the medial axis transformation (MAT), the results obtained by the automated transformation programs frequently require further modifications to meet the idealization rules for simulation. To reduce the computing time of the automated transformation approach, the detailed features need to be removed before the transformation process is launched. Although the solid-based simulation method has recently become popular, the traditional medial-surface-based simulation method is still useful because this method can provide simulation results more rapidly without significant loss of accuracy. Therefore, if the idealized models for both approaches can be readily provided at various levels of detail and/or abstraction from the design model, the cycle time for the design-analysis iteration can be reduced.

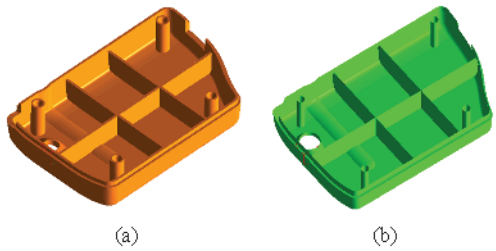

Fig. 2. An example of solid and abstract models for injection molding simulation and structural analysis: (a) a detailed solid model for design, (b) an abstracted sheet model for analysis.

To meet the above requirements, we have introduced 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 an NMT part master model, and for specific levels of detail and abstraction, analysis models of solid or NMT representation are provided immediately from the master model. The proposed approach is expected to integrate the CAD and CAE systems for the realization of concurrent engineering methodology.

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 design-analysis system was designed. It describes the functional requirements, the adopted design-analysis integration approach, and the final system architecture. Section 4 describes the feature-based NMT modeling for the creation and manipulation of part master models. Section 5 describes how analysis models at various levels of detail and abstraction are extracted from the master model by using multi-resolution and multi-abstraction modeling techniques. Conclusions are given in Section 6.

2. Related work

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

2.1 Design of injection molding parts

Intelligent injection molding product design systems have been studied extensively. Huh and Kim [1] developed a knowledge-based CAD system to support the initial design of injection molding products. This system contains two components: an expert system for the optimal design of ribs and gates, the so-called RIBBER and GATEWAY, and a three-dimensional geometric modeling system to represent the optimal design as solid models. To develop the expert system, they used empirical equations and knowledge of design of ribs and bosses, and extracted the rules for the knowledge-based modules. Ishii et al. [2] proposed a design system based on design compatibility analysis (DCA), which provides the framework for the knowledge-based evaluations of the clumps. DCA applies qualitative ratings to expert knowledge to determine the rating for a design. DCA aims to model a design review in which various experts from different fields rate a design based upon their own specific knowledge. DCA has proven its worth in many applications, including injection molding design, process selection, contact stress design, and serviceability design. Gadh et al. [7] emphasized the role of the design systems. Their system used experts' knowledge to judge the moldability of products as an alternative to numerical analysis systems. They also mention the representation and extraction of features for knowledge-based expert systems.

For efficient design of injection molding parts, feature technology is essential. Fortunately, feature-based design capabilities are available in most commercial CAD systems. The feature recognition and extraction technology is also useful for automated abstraction of analysis models, usually suppressing the details in the unit of the feature. A comprehensive survey of feature technology is given in Ref. [8].

To implement an integrated environment for design and analysis, the NMT modeling technology is used. Since an NMT model can represent any combination of wireframe, surface, solid, and cellular models in a unified data structure, it can be used to represent both design models and analysis models in an integrated modeling environment. Several data structures have been proposed to represent NMT objects [9, 10]. Boolean operations on NMT models can be implemented based on the merge & select algorithm [11], 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 [12] but also efficient extraction of geometric models at various levels of detail in multi-resolution solid modeling [13-15].

2.2 Analysis of injection molding process

The injection molding process is composed of a series of filling, packing and cooling processes. There has been considerable research to predict defects of injection molding products and to find optimal injection molding conditions [4-6]. Such research has resulted in various commercial CAE systems: Moldflow developed by Austin et al. [16], C-Mold developed by Wang et al. through the Cornell Injection Molding Program [6], and CAPA and MAPS-3D developed by VMTech [17]. These systems provide simulation capabilities for the entire molding cycle including the filling, packing, and cooling stages. Recently, Moldflow has been equipped with 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, significantly decreasing the model preparation time [16]. MAP-3D also provides full 3-D simulation capabilities [17]. Detail-removed models and mid-surface models, however, are still useful for the reduction of computation time and storage without significant loss of accuracy.

A simplified solid model for analysis is obtained by ignoring or suppressing small geometric details present in the part solid model. Expert systems extract form features from a CAD model, and then selectively suppress the uninteresting features for the generation of the analysis model [18, 19]. Fourier transformation is used for geometric detail suppression [20]. Clustering methods have also been used to simplify CAD models to prepare them for meshing [21]. Recently, a new metric system based on filleting has been developed to rate the detail level of the boundary entities, and to decompose a solid into detail features [22].

For the reduction of computation time and storage in analysis, solid models are frequently converted to appropriate lower-dimensional models, such as wireframes or sheets, by using the dimension reduction technology. Although expert systems have been used to select appropriate modeling abstractions [18], these selection methods are not general and do not provide enough flexibility. The medial axis transform (MAT)

[23], 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 [24, 25]. The mid-surface abstraction approach [26] has been suggested to overcome this problem. Recently, there was an attempt to use a morphological analysis of the solid model for not only simplification and idealization but also modification [27].

The process of detail removal and dimensional reduction for transformation of a solid design model to an NMT analysis model can be conducted systematically by adopting the feature-based multi-resolution and multi-abstraction modeling technology. The feature-based multi-resolution modeling of solids was initially proposed by Choi et al. [28]. In this approach, a conventional solid data structure is used as a topological framework for representing multi-resolution solid models. However, this approach is computationally expensive and does not allow arbitrary rearrangement of additive or subtractive features. For efficient extraction of models at various levels of detail, an approach using an NMT model of a cellular structure was introduced for multi-resolution representation [29]. This cellular NMT modeling approach was later applied to the progressive transmission of solid models through a network for network-based collaborative design [13]. Recently, the concept of the effective volume of features was introduced so that valid solids can be provided for an arbitrary rearrangement of features, regardless of the feature type [14]. The multi-resolution modeling technique was extended to multi-abstraction modeling technique by Lee [15]. In multi-abstraction modeling, the dimensionality of the feature is varied at different levels of abstraction. This technique can be used to integrate CAD and CAE systems in a wide range of engineering fields including injection molding product design.

2.3 Integration of design and analysis

The current CAD and CAE integration approaches are CAD-centric and CAE-centric, and CAD-CAE-integrated [15, 30]. 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 design models. In the CAD-CAE integrated approach [15], different types of geometric models are simultaneously created for design and analysis for each feature modeling operation, and merged into an NMT part master model. For a given level of detail and abstraction, 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 has been a challenge to apply the CAD-CAE integrated method to a specific engineering field like 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 to support the feature and solid models for the CAD systems as well as to support the abstract solid or NMT models for the 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 of a plastic part, to satisfy the given functional requirements of the part, the main shape of the part is first determined, and then the sizes and locations of the sub-features, such as ribs and bosses, are determined [1]. Thus, the three-dimensional CAD system must have design-with-feature capabilities for plastic part design.
- **Thin-walled part modeling capabilities:** The plastic parts usually have thin and constant thickness walls. Therefore, the system should have powerful modeling capabilities to deal with thin-walled solid models [31]. Currently, most CAD systems provide the user with shell-thickening or solid-shelling operations for thin-walled solid modeling, but these operations are limited to simple shapes.
- **Non-manifold topological representation:** The system should also be able to efficiently represent not only solid models for design but also abstract models for analysis. The system should be able to derive shell meshes on the medial surface of a part easily so that quick analysis results can be obtained for initial part design. To generate shell meshes, first, the main shape of a part is converted to a sheet model of the mid-surface, and then sub-features are converted to sheets or wireframes de-

pending on the mesh size. Therefore, NMT representation is essential to represent analysis models composed of solids, sheets and wireframes.

- **Simplification and idealization capabilities:** Current commercial analysis packages require CAD solid models or mid-surface models as geometric input. However, the simplification and idealization capabilities that provide various levels of simplified and abstracted models are still essential for analysis packages because they can 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. In the CAD-CAE integrated approach [15], different types of geometric models for design and analysis are merged into an NMT part master model, and then, for a given level of detail (LOD) and level of abstraction (LOA), an appropriate design or analysis model is extracted from the master model.

The architecture of the system adopting the integrated CAD-CAE approach shown in Fig. 3 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 the form features in their life cycle. It creates, deletes, and modifies the form features in the part model, and maintains the information in a hierarchical relationship among the features. This module sends messages to create and delete the geometric models of form features to the non-manifold geometric modeler.
- **Feature-based idealization module:** This module 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 [10, 32] 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. In particular, this kernel manages the merged-set models of parts, which have been generated by merging all the 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 [31].

3.3 Design and analysis cycles

As illustrated in Fig. 3, the iterative design process of the CAE/CAE-integrated system consists 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 these models as the base feature. Next, the user creates sub-features sequentially. All geometric models of the sub-features for design and analysis are merged into a master part model.

(Phase 2) Idealization: The feature-based idealization module is executed in this phase. If the user specifies a detail level, then the simplified solid model corresponding to the detail level is extracted from the master model by using the multiresolution modeling technique. This simplified model can be used for an analysis system that requires a CAD solid model as geometric input. If an analysis system requires an idealized low-dimensional model, then such a model can be extracted from the master model through the abstraction process. This idealization process via abstraction is usually followed by mesh generation, which can be performed in either the CAD system or the CAE system. The analysis model in the form of an NMT model or a mesh model is transferred to the CAE system.

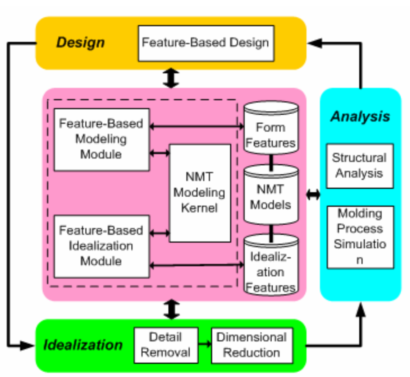

Fig. 3. Design process in the CAD/CAE -integrated approach.

(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 for injection molding parts

4.1 Representation of parts

The part model contains feature and geometric information. Features are connected to each other graphically in a parent-child relationship. The base feature for the main shape of the part is the starting node of the graph. The sub-features, such as ribs, bosses, holes, and snapshots, are auxiliary features for reinforcement or assembly of the product. The geometric model is represented by a merged-set model, which 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 the 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. Generally, form features are classified into three basic types: volume, transition, and pattern features. To facilitate the construction of the merge-set model, in this paper, form features are described using volumetric representation, and are classified into additive and subtractive features. The transition features and the feature patterns are converted to additive or subtractive volume features.

A representation of an example part is shown in Fig. 4. The features are connected to each other graphically in a parent-child relationship. Each feature points to a solid model 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 the mesh size. In this system, all possible abstract models are stored in the merged-set model of the part, and one of them satisfying a condition is selected and extracted.

4.2 Feature creation and deletion

In the design phase, part master models are created or modified with 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, any feature can be removed by using the feature deletion function, and modified with the feature modification function.

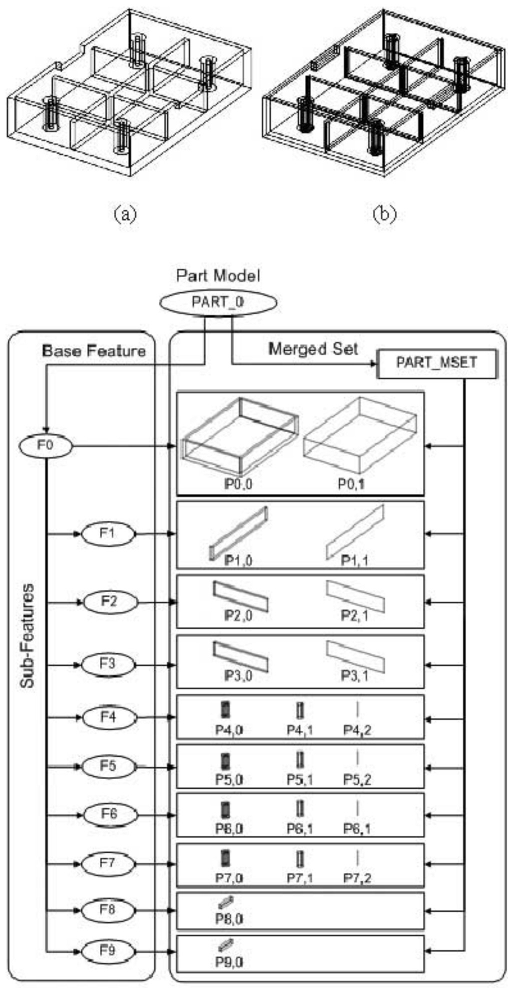

Fig. 4. Example of part representation: (a) a feature-based solid model, (b) a merged-set of the geometric models of features, (c) a part model composed of a feature graph and an NMT B-rep database.

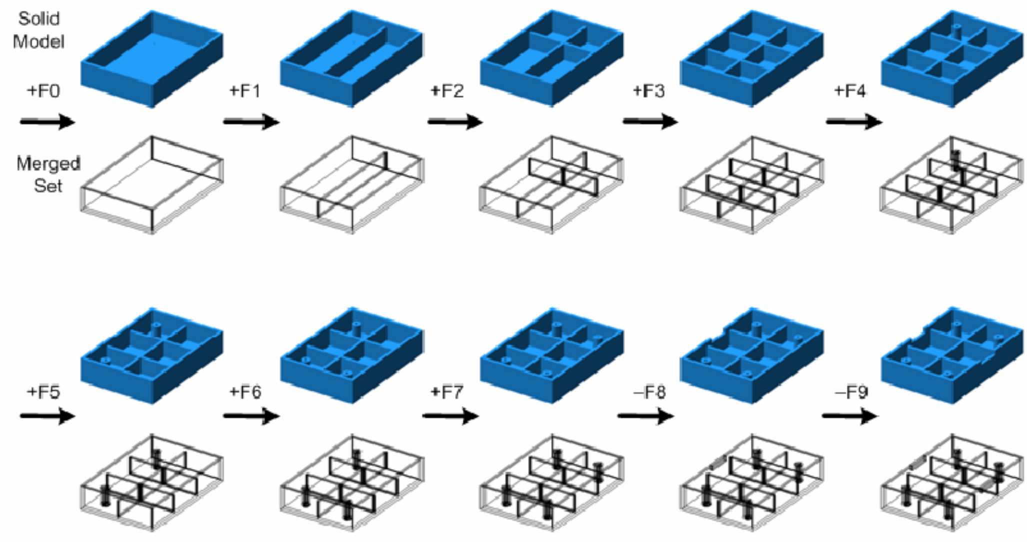

Fig. 5. Feature-based modeling procedure for the example model shown in Fig. 4.

- **Base feature creation:** The user creates a solid model and an abstract model for the main shape of a 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, which transforms a sheet into a solid with the given thickness [10, 31, 32]. 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 half 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 model in the system creates the merged-set model.
- **Sub-feature creation:** 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 graphically. Then, the system creates the solid and abstract models according to the shape variables, and merges these two models into the master part model, which is the merged-set NMT model. At this point, to prevent discontinuities in the 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 between the delete-specified feature and the other features. In this system, if a parent feature is deleted, 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 master part model stores all the topological entities and their historical record created during design.
- **Feature modification:** When the user modifies the parameters and/or the location and orientation of a feature, the system updates the feature information and the geometric data. To update the geometric data, the system first removes the existing geometric data related to the feature, and then

creates new geometric data of the modified feature and implants them into the merged-set model.

Fig. 5 shows the modeling history of ten features in the creation of an example solid model shown in Fig. 4. 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, one solid model is shared by the analysis model and 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 (–).

5. Idealization

The idealization process for the extraction of analysis models consists of two stages: detail removal and dimensional reduction. The multi-resolution modeling technique for feature-based solid models [14] is adopted for detail removal at various LODs. The most advanced multi-resolution modeling technique based on the history-based selective Boolean operations is applied for detail removal. The multi-abstraction modeling technique for feature-based NMT models [15] is introduced for dimensional reduction at various LOAs.

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 a part to analyze the part's stress and strain distribution or to simulate the molding process, the detailed features have to be suppressed. For instance, a hole whose diameter is smaller than the mesh size is removed for molding flow simulation.

The detail removal process can be explained by using the example shown in Fig. 4. The process consists of the following three steps.

(Step 1) User input: the user specifies the threshold values to determine whether a feature is to survive or not. Typical values are the mesh size and the feature volume.

(Step 2) Selection of features: the system selects the features that pass the threshold of survival.

(Step 3) Selection of topological entities: The system selects the topological entities constituting the Boolean result. For this purpose, the system first composes a string of a sequence of the Boolean operations with the surviving features in the original creation order of the features. The model is exactly the same as that of the Boolean operations on the effective volumes of the features rearranged in the order of feature significance [33]. For example, if the features F0, F1, F2, F3, F8, F9 are selected, then "P0,0 + P1,0 + P2,0 + P3,0 – P8,0 – P9,0" is composed. Next, the string is delivered to the selection module, which selects the topological entities constituting the Boolean result and displays them on the screen.

The simplified solid model can be used for a CAE system that requires CAD solid models as geometric input. If the user wants to reduce the dimensionality of the simplified solid model, he/she can execute the dimensional reduction process successively.

5.2 Dimensional Reduction

If the user wants to use any abstract analysis model of a part for structural analysis or molding process simulation, the dimensional reduction process has to be executed. The criteria of LOA are application-dependent. In structural analysis, the aspect ratio is a good criterion to determine the abstraction level [24, 31]. Depending on the aspect ratio, a solid object may be abstracted to a beam element or a plate element. In injection molding simulation, the ratio of the feature's key dimension and the mesh size can be the 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. A 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 of a part, and two node meshes are used to represent bosses, pins, runners, and gates.

In the dimensional reduction process, the system selects and marks the topological entities that contribute to the construction of the abstract model for analysis. For a given LOA criterion, the system selects the appropriate abstract model for each feature that survived in the detail reduction process. The selection method is implemented in the class of each form feature. A string representing a sequence of the Boolean opera-

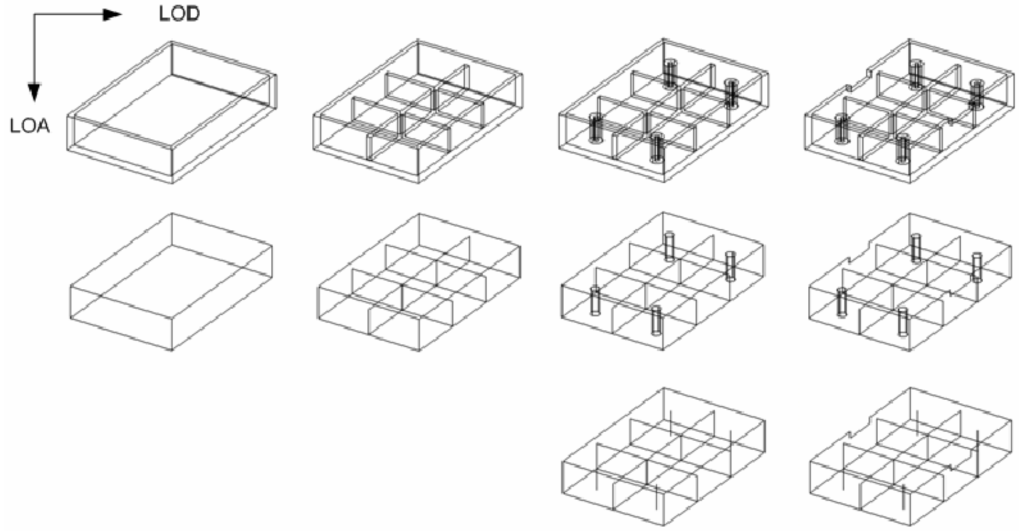

Fig. 6. Idealized models for the example part.

tions performed on the selected abstract models is composed and sent to the selection module, which then marks and displays the topological entities constituting the Boolean result. Fig. 6 presents the idealization results of an example part model for various LODs and LOAs.

Once the idealization process is finished for mesh generation or transfer to a CAE system, a clean geometric model for analysis needs to be created from the selected topological entities of the merged-set model. There are two methods to create a clean analysis model: one, to copy the merged set and delete the unselected entities, and the other, to create a new model using the NMT Euler operators. Since the former is easier than the latter, we chose the former method. Finally, this clean analysis model is transferred to CAE systems directly, or to a CAE pre-processor for mesh generation.

6. Conclusions

We have proposed a new method for the integration of design and analysis models for injection molding parts using the NMT model and the multi-resolution and multi-abstraction modeling techniques. In the proposed system, various different geometric models for design and analysis are simultaneously created and merged into an NMT master part model, and for a specific level of detail and abstraction, an analysis model in solid or NMT representation is provided immediately from the master part model. In addition, the NMT B-rep allows easy implementation of the immediate deletion and interaction detection of features, which are difficult to implement in a solid modeler. In addition, our NMT kernel provides sheet modeling capabilities and the transformation function, which transforms a sheet to a solid, to facilitate modeling of thin-walled parts. Moreover, this system, which is implemented using object-oriented programming technique, allows the user to define and add a new feature into the feature library without the need to change the source code of the existing system. Therefore, the proposed approach is expected to integrate the CAD and CAE systems for the realization of concurrent engineering methodology.

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) enlargement of the feature library for the feeding system to include features such as gates and runners, (3) development of a more robust embedding method of abstract models (currently, the abstract models for an additive sub-feature are extended and trimmed by the abstract models of the feature to be attached), and (4) evolution of the system into a more intelligent one by adopting an expert system to evaluate the results of design and analysis.

Acknowledgments

This work was supported by research program 2006

of Kookmin University in Korea.

References

[1] C. G. Armstrong, Modeling requirements for finite-element analysis, *Computer-Aided Design*, 26 (1994) 573-578.

[2] C. G. Armstrong, R. M. McKeag, H. Ou. and M. A. Price, Geometric Processing for Analysis, *Proc. of Geometric Modeling and Processing*, (2000) 45-56.

[3] M. Belaziz, A. Bouras and J. M. Brun, Morphological analysis for product design, *Computer-Aided Design*, 21 (2000) 377-388.

[4] J. Cagan and V. Genberg, PLASHTRAN: an expert consultant on two-dimensional finite element modeling techniques, *Engineering with Computers*, 2 (1987) 199-208.

[5] W. W. Charlesworth and D. C. Anderson, Applications of non-manifold topology, *Proc. of International Computers in Engineering Conference and the ASME Database Symposium*, (1995) 103-112.

[6] D. H. Choi, T. W. Kim and K. Lee, Multiresolutional representation of b-rep model using feature conversion, *Transactions of the Society of CAD/CAM Engineers*, 7 (2002) 121-130. (in Korean)

[7] G. A. Crocker and W. F. Reinke, An editable non-manifold boundary representation, *IEEE Computer Graphics & Applications*, 11 (1991) 39-51.

[8] R. Gadh, M. A. Hall, E. L. Gursoz and F. B. Prinz, Knowledge driven manufacturability analysis from feature-based representations, *Proc. of the Winter Annual Meeting of the ASME*, DE-Vol.21/PED- Vol. 36 (1989) 21-34.

[9] S. Gordon, An analyst's view: STEP-enabled CAD-CAE integration, *Presentation materials of NASA's STEP for Aerospace Workshop*, (2001) 16-19.

[10] B. L. Gregory and M. S. Shephard, The generation of airframe finite element models using an expert system, *Engineering with Computers*, 2 (1987) 65-77.

[11] C. A. Hieber and S. F. Shen, A finite-element/finite-difference simulation of the injection-molding filling process, *Journal of Non-Newtonian Fluid Mechanics*, 7 (1980) 1-32.

[12] Y. J. Huh and S. G. Kim, Ribber: a knowledge-based synthesis system for ribbed injection molded parts, *Proc. of the Winter Annual Meeting of the ASME*, PED-Vol.36 (1989) 195-204.

[13] K. Ishii, L. Hornberger and M. Liou, Compatibility-based design for injection molding, *Proc. of the Winter Annual Meeting of the ASME*, DE-Vol.21/PED-Vol. 36 (1989) 153-160.

[14] H. S. Lee, H. C. Sin and S. G. Kim, Integrative boundary pressure reflection method for injection mold filling, *Polymer Engineering and Science*, 30 (1990) 1513-1522.

[15] J. Y. Lee, J.-H. Lee, H. Kim and H. S. Kim, A cellular topology-based approach to generating progressive solid models from feature-centric models, *Computer-Aided Design*, 36 (2004) 217-229.

[16] K. Lee, *Principles of CAD/CAM/CAE Systems*, Addison Wesley Longman, Inc., 1999.

[17] S. H. Lee, Offsetting operations on non-manifold boundary representation models with simple geometry, *Proc. of Fifth Symposium on Solid Modeling and Applications*, (1999) 42-53.

[18] S. H. Lee, Feature-based multiresolution modeling of solids, *ACM Transactions on Graphics*, 24 (4) (2005) 1417-1441.

[19] S. H. Lee, A CAD-CAE integration approach using feature-based multi-resolution and multi-abstraction modelling techniques, *Computer-Aided Design*, 37 (2005) 941-955.

[20] S. H. Lee, K. Lee and S. Kim, History-based selective Boolean operations for feature-based multi-resolution modeling, *Lecture Notes in Computer Science*, 3980 (2006) 459-468.

[21] S. H. Lee and H.-S. Kim, Sheet modeling and thickening operations based on non-manifold boundary representations, *Proc. of ASME Design Engineering Technical Conferences*, (2001) DETC-2001/DAC-21010.

[22] S. H. Lee and K. Lee, An integrated CAD system for mold design in injection molding process, *Proc. of the Winter Annual Meeting of the ASME*, PED-Vol.32 (1988) 257-271.

[23] S. H. Lee and K. Lee, Partial entity structure: a compact boundary representation for non-manifold geometric modeling, *ASME Journal of Computing & Information Science in Engineering*, 1 (2001) 356-365.

[24] S. H. Lee, K.-S. Lee and S. Park, Multiresolution representation of solid models using the selective Boolean operations, *Proc. of Korean Society of Precision Engineering Conference* (2002), KSPE 02S179 833-835. (in Korean)

[25] Y.-G. Lee and K. Lee, Geometric detail suppression by the Fourier transformation, *Computer-Aided Design*, 30 (1998) 677-693.

[26] B. Li and J. Liu, Detail feature recognition and

decomposition in solid model, *Computer-Aided Design*, 34 (2002) 405-414.

[27] Moldflow, http://www.moldflow.com

[28] J. M. Reddy and G. M. Turkiyyah, Computation of 3D skeletons using a generalized Delaunay triangulation technique, *Computer-Aided Design*, 27 (1995) 677-694.

[29] M. Rezayat, Midsurface abstraction from 3D solid models: general theory and applications, *Computer-Aided Design*, 28 (1996) 905-915.

[30] J. J. Shah and M. Mäntylä, *Parametric and feature-based CAD/CAM*, John Wiley & Sons, Inc., (1995).

[31] A. Sheffer, Model simplification for meshing using face clustering, *Computer-Aided Design*, 33 (2001) 925-934.

[32] VMTech, http://www.vmtech.co.kr.

[33] K. K. Wang, et al., Integration of CAD/CAM for injection-molded plastic parts, *CIMP Progress Report*, No. 13, (1987).

Sang Hun Lee received his B.S., M.S., and Ph. D. degrees in Mechanical Design and Production Engineering from Seoul National University, Korea, in 1986, 1988, and 1993, respectively. Dr. Lee is currently a Professor at the School of Mechanical and Automotive Engineering at Kookmin University in Seoul, Korea. His research interests include CAD/ CAM, human-centered design and engineering, digital human modeling and simulation, computer-aided automotive design and manufacturing., and computer-aided tooling design.