CAD and CAE Integration Using Multi-Abstraction Mon-Manifold Modelling Method

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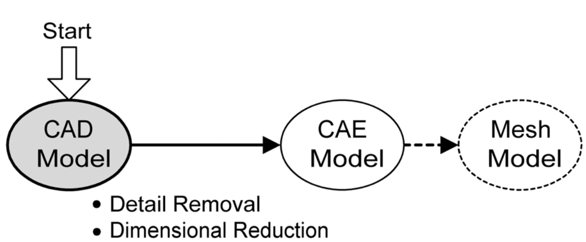
ABSTRACT

In spite of the widespread use of CAD systems for design and CAE systems for analysis, the two processes are not well integrated because CAD and CAE models inherently use different types of geometric models and there currently exists no generic, unified model that allows both design and analysis information to be specified and shared. In this paper a new approach called the CAD/CAE-integrated approach is proposed that creates and manipulates a single master model containing different types of all of the geometric models required for CAD and CAE. Both a solid model (for CAD) and a non-manifold model (for CAE) are immediately extracted from the master model through a selection process. If a design change is required, the master model is modified by the feature modelling capabilities of our system. As a result, the design and analysis models are modified simultaneously and maintained consistently. This system also supports feature-based multi-resolution and multi-abstraction modelling capabilities providing the CAD model at different levels of detail and the CAE model at various levels of abstraction.

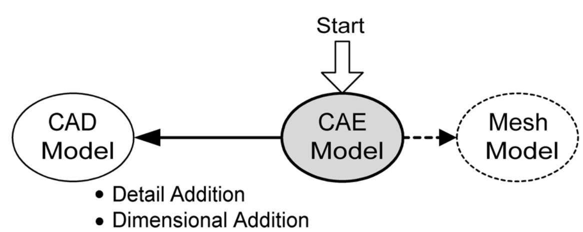
Keywords: Integration of CAD and CAE, Multi-resolution; Level of detail; Level of abstraction; Feature; Solid; Non-manifold.

1. INTRODUCTION

Recently, three-dimensional CAD systems based on feature-based solid modelling 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. Currently, as illustrated in Fig. 1, there are two approaches to CAD and CAE integration: CAD-centric and CAE-centric [11].



(a)



(b)

Fig. 1 Current methods of CAD and CAE integration: (a) CAD-centric; (b) CAE-centric.

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. This method has been widely adopted in the current design process. Finite element analysis (FEA) is one of the most popular CAE methods. Unfortunately, design models created by CAD systems are often unsuitable for analysis needs. Therefore, an appropriate idealization process including detail removal and dimensional reduction is indispensable for analysis models [1]. This abstraction task is a significant obstacle to CAD and CAE integration as it is a non-intuitive and time-consuming job. To solve this problem, there have been many research efforts to automate the abstraction process, for instance, using automated medial axis transformation (MAT) of solid models [3, 24, 25]. However, at present, only limited automated capabilities exist, and these require improvement.

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. As illustrated in Fig. 1(b), the design model is modified by adding detail and dimensional information to the analysis model. This approach of adding detail and dimensionality after analysis is contrasted to the CAD-centric approach that requires de-featuring of CAD details for FEA-specific geometry and analysis models. Automated and semi-automated procedures are desirable for this CAD-centric approach. An automated 'solid-on-demand' transformation capability is required to electronically send the CAE model to the CAD system. Otherwise, design personnel create the solid geometry model from scratch.

Both of these approaches require duplicate efforts to create and consistently maintain two different models for one product. Lack of automated transformation tools between design and analysis models often leads to the creation of the other type of model from scratch. This manual transformation is a significant bottleneck in CAD–CAE integration. In addition, in engineering analyses, it is often required to change the level of detail (LOD) and/or the level of abstraction (LOA) of the analysis model. Whenever the LOD or LOA is altered, the transformation process must be carried out again. As a solution to these problems, a common modelling environment and bi-directional CAD–CAE integration has been addressed. Not only does the system allow the CAD system to generate analysis models automatically, it also allows the CAE system to modify the part geometry automatically and to conduct new analyses. The entire process is iterated until the specified quality measurement criteria have been met.

To achieve this goal, we proposed a new method called the CAD/CAE-integrated approach to provide a unified and concurrent modelling environment for seamless CAD–CAE integration. Figiure 2 shows the data flow in this approach. The underlying technologies for this approach are design-by-feature, non-manifold topological (NMT) modelling, multi-resolution solid modelling, and multi-abstraction NMT modelling, which is newly proposed in this paper. In this approach, different types of geometric models are simultaneously created for design and analysis for each feature modelling operation. These are merged into a part master model, which is an NMT model called a merged set [10]. Solid models at various LODs can be immediately extracted from the master model. Moreover, for a specific LOD, abstracted NMT models at various LOAs can be rapidly extracted from the master model and transferred to CAE systems. For design changes, modification of the master model results in the simultaneous and consistent modification of the design and analysis models.

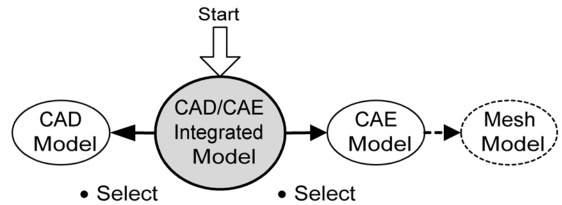


Fig. 2 The CAD/CAE-integrated approach proposed in this paper.

The remainder of the paper is organized as follows. Section 2 first reviews the detailed CAD–CAE or CAE–CAD transformation processes for each integration approach, and then surveys the related work on the component technologies used in these processes. Section 3 describes the overall process and the system architecture in our approach, and Section 4 describes the feature-based NMT modelling system for the creation and manipulation of part master models. Section 5 introduces the foundations of multi-resolution and multi-abstraction NMT modelling. These are defined as the effective primitives of feature, which enable arbitrary rearrangement of NMT features, and the idealization feature table, which facilitates implementation of multi-resolution and multi-abstraction modelling. Section 6 describes the detailed algorithms for multi-abstraction and multi-resolution modelling, which enable extraction of design and analysis models at various LODs and LOAs. Section 6 also presents a case study. Some conclusions and discussions of future work are given in Section 7.

2. RELATED WORK

Various CAD component technologies are necessary for CAD–CAE or CAE–CAD transformation processes in the CAD–CAE integration approaches described in the previous section. The related technologies and their literature survey are as follows.

- **Feature-based design and feature recognition**: These methods have been the focus of extensive research over the past decade and great strides have been made. In particular, most commercial CAD systems support feature-based design at present. Feature recognition and extraction technology are indispensable for automated abstraction of analysis models, as details to be suppressed are recognized by feature recognition techniques.

For a comprehensive survey of feature technology, see [26].

- **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 [6, 12]. Fourier transformation has also been introduced for geometric detail suppression by Y.G. Lee et al. [21] Clustering methods have also been presented [27] that are suitable for the simplification of CAD models in preparation for meshing. Recently, Li and Liu [22] 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.
- **Dimensional reduction**: Solid models are converted to appropriate lower-dimensional models, such as wireframes or sheets, using this technology. In FEA, wireframes correspond to beams while sheets correspond to plates or shells. There have been attempts to use expert systems for selecting appropriate modelling abstractions [6, 12], however these methods are not general and do not provide enough flexibility. The medial axis transform (MAT) [24], 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 [25] 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. This method also allows the creation of a solid model based on the idealized one, by using parameterized reconstruction operators.
- **Dimensional addition**: This technique for creating solids from the abstract NMT models used in the preliminary design is necessary in the CAE-centric approach, but is not well supported in current CAD or CAE systems [2]. Sheet thickening, NMT offsetting, and skeleton refleshing operations can be used for dimensional addition. Sheet modelling and thickening operations were initially developed based on those of a solid B-rep [23]. Later, the author developed the offsetting algorithm for NMT models [16], and adapted it for sheet thickening [18]. Recently, the skeleton refleshing technique of reconstructing an object from skeletal data has been explored by several researchers [5, 28]. Various skeleton-based editing operations that alter the skeletal data before refleshing have also been explored [5]. However, current refleshing methods only produce approximate models, while the sheet thickening algorithms generate precise CAD models.
- **Non-manifold topological (NMT) modelling**: The NMT model can represent any combination of wireframe, surface, solid, and cellular models in a unified data structure. Additionally, Boolean operations are closed in this NMT representation domain, in contrast to those on solid models [7, 15]. Several data structures have been proposed to represent NMT objects [15, 29]. Boolean operations on NMT models can be implemented based on the merge & select algorithm [10], 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 allows the user to modify the Boolean operators or their order of occurrence even more easily, and to select, using a CSG tree, a subset of the primitives in the merged set. Using this property, both the efficient detection of feature interactions and efficient feature deletion are possible in feature-based design systems based on the NMT representation [7]. In multi-resolution solid modelling, this algorithm enables efficient extraction of geometric models at various levels of detail [14, 17, 20].
- **Multi-resolution modelling**: Much research has focused on multi-resolution modelling for polyhedral models in computer graphics [9]. In contrast, Choi et al. [8] proposed a multi-resolution modelling method for feature-based solid models. In this approach, the multi-resolution model is represented by a feature tree in which features are rearranged according to criteria based on measures of LOD. If a simplified model at a certain LOD is required, the system prunes the branches of the feature tree and performs boundary evaluation to obtain a corresponding solid model. The main applications of this approach are engineering design and analysis. 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, the author introduced

NMT models of a cellular structure for the multi-resolution representation [20]. J.Y. Lee et al. [14] applied this NMT approach to the progressive transmission of solid models through a network, for network-based collaborative design. Recently, the author introduced a measure of the effective volume of features to provide valid solids for an arbitrary rearrangement of features, regardless of feature type [17].

3. OVERALL PROCESS AND SYSTEM ARCHITECTURE

A feature-based NMT modelling system has been implemented to verify the CAD/CAE-integrated approach. The architecture of the system is shown in Fig. 3. It consists of three main modules: a feature-based modelling module, a feature-based idealization module, and an NMT modelling kernel. The feature-based modelling module manages the library and database of form features in their life cycle. The feature-based idealization 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 abstracted analysis models. The NMT modelling kernel creates and manipulates all of the geometric models for the design and analysis stages and for other downstream applications.

The iterative design process using this system is illustrated in Fig. 3, and its application scenario is as follows. First, the user conducts a part design using the feature-based modelling module. For each feature model, all geometric models of the feature required for the design and analysis are merged into the part master model.

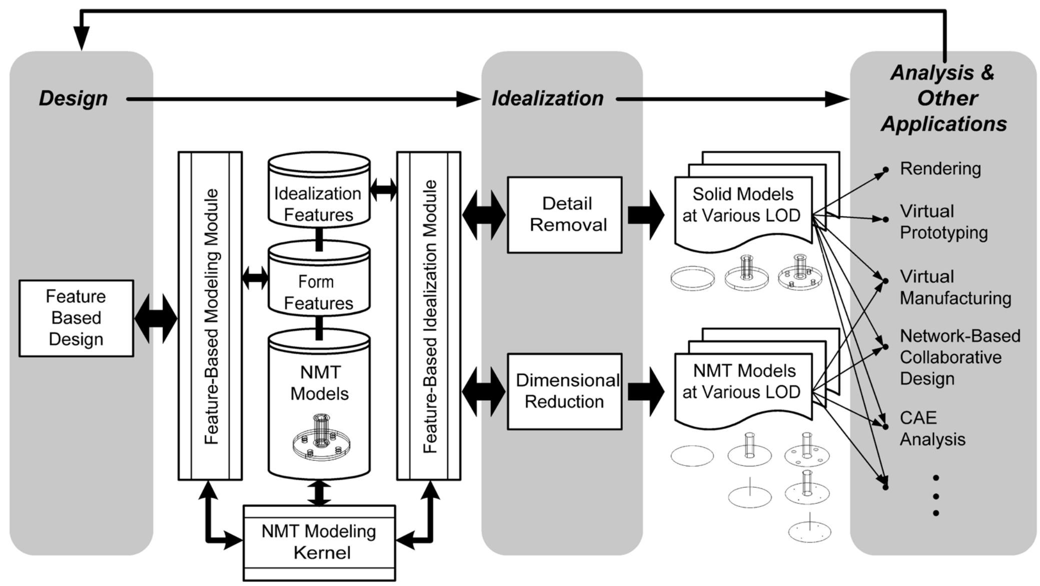


Fig. 3 Design process in the CAD/CAE-integrated approach.

Next, the user executes the feature-based idealization module. If the user specifies an LOD, then the corresponding solid model is extracted from the master model. It is also possible to extract a series of solid models at higher or lower LODs. These multi-resolution models can be used for various applications such as rendering, network-based collaborative design, digital mock-up, and virtual manufacturing.

Finally, the user specifies the LOA for the current LOD model, and the corresponding abstract model is extracted from the master model. Of course, a series of LOA models can be extracted consecutively. A mesh model is generated by applying an automated mesh generation procedure to this model, and this is transferred to a CAE system to allow CAE analysis to be conducted. The user iterates the whole process until the analysis result is satisfactory.

3.1 Design

In the design phase, the part master models are created or modified using the feature-based NMT modelling system. The feature-based modelling process can be represented by a CSG tree as shown in Fig. 4. The terminal nodes of the tree describe the primitives of the features, while the internal nodes represent Boolean operations. The Boolean operation of a feature is determined by the type of the feature. If a feature is additive, the operation is union ($\cup$). If subtractive, the operation is difference ($-$). Figure 4 shows a feature tree that can be used to create an example solid model by applying three features. Multiple geometric models are embedded into the master model in each feature modelling 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.

Figure 5 shows the merged set of the three features shown in Fig. 4. This model will be used throughout this paper to explore the proposed CAD/CAE-integrated approach.

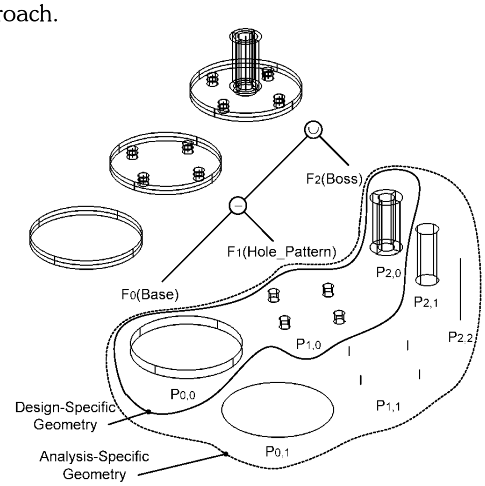


Fig. 4 An example of feature-based solid modelling.

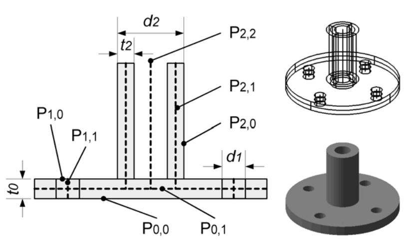


Fig. 5 Merged set of the features shown in Fig. 4

3.2 Idealization

To extract abstract analysis models, the idealization process consists of detail removal and dimensional reduction phases. The multi-resolution modelling technique for feature-based solid models [17] is adopted for detail removal at various LODs. The multi-abstraction modelling technique for feature-based NMT models, which is newly proposed in this paper, is introduced for dimensional reduction at various LOAs.

(Phase 1) Detail removal: LOD models are first defined automatically by the system or manually by the user. One of the representative criteria of the LOD is the volume of the feature. The model at the highest LOD is coincident with the original part shape. As illustrated in Fig. 6, a coarser shape is obtained by decreasing the LOD. The user then selects a simplified model at some appropriate LOD. For instance, in Fig. 6, the user selects the simplified model at LOD = 1, where the hole-pattern feature is removed.

(Phase 2) Dimension reduction: The LOD model selected in Phase 1 is abstracted by reducing the dimensionality of feature shape. As illustrated in Fig. 6, a more abstract model is obtained by increasing the LOA. The user chooses an idealized model at some appropriate LOA. For instance, in the process shown in Fig. 6, the user chooses an abstracted model at LOD = 1 and LOA = 2, where the base and the boss features are abstracted to sheet models.

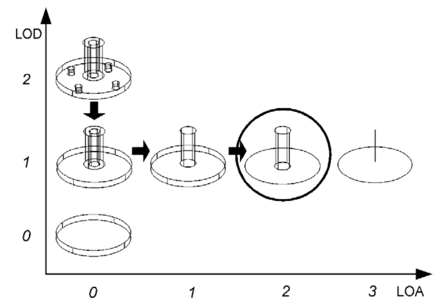


Fig. 6 Idealization process using multi-resolution and multi-abstraction modelling techniques.

4. DATA STRUCTURE

The part model contains the feature and geometry information. Figure 7 shows the schematic diagram of the part model described in the EXPRESS-G style. This diagram represents only the entities and attributes referred to in this paper. The part model also records the feature modelling history in its attributes. The following section explains the features, together with the merged set introduced in the system, in more detail.

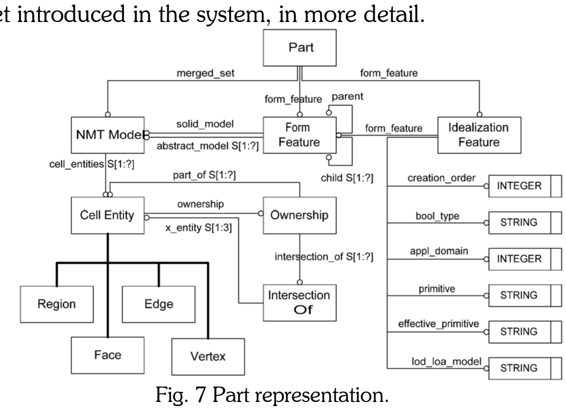


Fig. 7 Part representation.

4.1.Feature Representation

4.1.1. Form Features

Feature taxonomies can be based on either product categories, intended applications of the features, or feature shapes. Several taxonomy schemes have been proposed for classification entirely by feature shape [26]. For instance, Part 48 of STEP categorizes form features 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.

In our approach, all possible abstract models for each feature are merged into the part model, and one of them is chosen to constitute an analysis model at a given LOA. The criteria of LOA are dependent upon a feature's dimensions and the analysis context. This topic is discussed in more detail in Section 6. The choosing method is implemented in the feature class.

To prevent discontinuities in analysis models, the dimensions of the feature abstract models may differ from those of the feature solid model. The abstract models for an additive feature are extended and trimmed by the abstract models of the feature to be attached. For instance, as illustrated in Fig. 5, the abstract models $P_{2,1}$ and $P_{2,2}$ of the feature F_2 are extended and trimmed by the abstract model $P_{0,1}$ of F_1.

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. If the automated embedding of an abstract model is difficult for a feature, an alternative is to allow some user interaction to define abstract models.

4.1.2. Idealization Features.

In order to facilitate the implementation of the idealization process, the idealization feature is introduced as an extension of the multi-resolution feature proposed in [17]. 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 include the pointer to the form feature, the creation order, the type of the Boolean operation, the application domain, the name of the feature primitive, the effective primitive of the feature, the definition of the LOD/LOA model, and so on.

For instance, when the example solid model is created as shown in Fig. 4, a list of the idealization features is filled like those shown in Table 1. In this table, the idealization features are initially arranged in the order of feature creation. The application domain is currently one of three cases: design, analysis, or design and analysis, and are denoted by *D*, *A*, or *D/A*, respectively. The effective primitive of each feature is assigned to the name of its solid model. This means that, in the case of the current feature arrangement, the whole of the feature geometry is used by the Boolean operations to extract LOD/LOA models. In the multi-resolution or multi-abstraction modelling processes, the related idealization features are extracted from the table in Table 1, before being rearranged in the order of LOD or LOA for the progressive generation of idealized models.

No	Feature Name	Creation Order	Bool	Appl. Domain	Primitive	Effective Primitive	LOD/LOA Model
0	Disk	0	+	D/A	$P_{0,0}$	$P_{0,0}$	
1	Disk	0	+	A	$P_{0,1}$	$P_{0,1}$	
2	Holes	1	−	D/A	$P_{1,0}$	$P_{1,0}$	
3	Holes	1	−	A	$P_{1,1}$	$P_{1,1}$	
4	Boss	2	+	D/A	$P_{2,0}$	$P_{2,0}$	
5	Boss	2	+	A	$P_{2,1}$	$P_{2,1}$	
6	Boss	2	+	A	$P_{2,2}$	$P_{2,2}$	

Tab. 1. Initial idealization feature table for feature modelling in Fig. 4

4.2. Non-manifold Topological Models.

A non-manifold data structure has been adopted as the topological framework for this system, and the *merge & select* algorithm [10] selected for boundary evaluation. The system has been developed based on the NGM (Non-manifold Geometric Modeller), which is a non-manifold modelling kernel developed by the author on the basis of the Partial Entity Structure [19]. The part master model has a merged set of all of the primitives of the features. In order to support the merge & select algorithm, the proposed data structure, as shown in the schematic diagram in Fig.7, stores the historical information in the Ownership attribute of the Cell Entity class.

5. IDEALLIZATION

5.1. Effective Primitive of Feature

For detail removal and dimensional reduction at various levels of detail and abstraction, the features need to be rearranged according to given criteria for level of detail and level of abstraction. However, if features are rearranged the resulting shape is different from the original, due to the non-commutative nature of the union and subtraction Boolean operations. Therefore, it is crucial to find a method that, for an arbitrary rearrangement of features, results in a final shape that is identical to the original shape and offers models having reasonable shapes at intermediate levels of detail.

To solve this problem, the author has previously introduced the concept of the effective volume of a feature [17], and developed an algorithm for feature-based multi-resolution modelling based on this effective volume. Here, the effective volume of a feature is defined as the actual volume, used as a tool body, of the Boolean operation for embedding the feature. However, this method was devised after considering only solid models. It is therefore necessary to extend the representation domain to the 3D NMT modelling space to apply dimensional reduction, as the abstract models are NMT models. The NMT model can also be defined as a point set over the R^3 space. Fortunately, the theorems proposed by the author in this paper can be readily extended to NMT models by simply replacing the volume with the 3D point set. This 3D point set is called *the effective primitive of the feature.*

5.2. Detail Removal using Multi-Resolution Solid Modeling Method.

Detail removal is the first phase of the part geometry idealization process. The process for detail removal consists of the following three steps.

(Step 1) The idealization features whose application domain involves design, denoted *D* or *D/A* in the table in Table 1, are extracted from the idealization feature list in the part master model.

(Step 2) The extracted idealization features are rearranged according to a given criterion of LOD. The volume of the feature is a criterion measure adopted frequently. Equation (4) is used to define the effective primitives of features after the rearrangement. A simplified solid model at each LOD is defined as a sequence of Boolean operations between the effective primitives.

(Step 3) The user selects a simplified model at an appropriate LOD.

The result of the extraction and rearrangement tasks for the example in Fig. 4 is shown in Table 2. The order of the features is changed to $F_0 \rightarrow F_2 \rightarrow F_1$. Accordingly, the effective primitive of F_1 is changed to $P_{1,0} - P_{2,0}$ following Eqn. (4). Nevertheless, in this case, $P_{1,0} - P_{2,0}$ is equivalent to $P_{1,0}$, as there is no intersection between $P_{1,0}$ and $P_{2,0}$. Figure 8 shows three different LOD models.

No	Feature Name	Creation Order	Bool	Appl. Domain	Primitive	Effective Primitive	LOD/LOA Model
0	Disk	0	+	D/A	$P_{0,0}$	$P_{0,0}$	$P_{0,0}$
1	Boss	2	+	D/A	$P_{2,0}$	$P_{2,0}$	$P_{0,0}+P_{2,0}$
2	Holes	1	−	D/A	$P_{1,0}$	$P_{1,0}-P_{2,0}$	$P_{0,0}+P_{2,0}-(P_{1,0}-P_{2,0})$

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

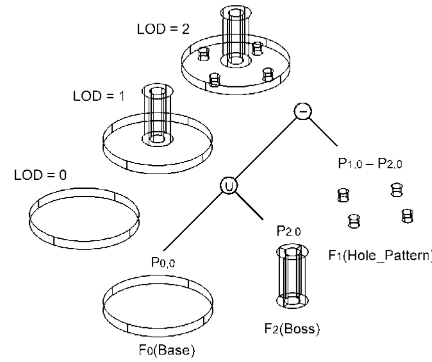


Fig. 8 The LOD models according to the idealization feature table in Tab. 2.

5.3. Dimensional Reduction using Multi-Abstraction NMT Modeling Method.

5.3.1 Multi-Abstraction NMT Modeling Method.

Once detail has been removed as required, the selected LOD and the idealization feature list for the design domain, $F^D = \{F_i^D\}_{i=0}^{LOD}$, are transferred to the dimensional reduction procedure. In the dimensional reduction process, for a given LOA, the corresponding abstract model is extracted through the following procedure.

(Step 1) Create an idealization feature list F^A and copy the contents of F^D .

(Step 2) For a given LOA, the system selects the appropriate abstract primitive model for each idealization feature F_i^A using the selection method in the form feature class.

(Step 3) Redefine the effective primitive and the LOD/LOA models by substituting the solid primitive name F_i^D with the abstract primitive name chosen in Step 2. For instance, if LOD is 1 and the abstract models for F_0 and F_2 are chosen as $P_{0,1}$ and $P_{2,1}$, then $P_{0,0}$ and $P_{2,0}$ in the table are substituted with $P_{0,1}$ and $P_{2,1}$ as shown in the analysis feature table in Table 3.

(Step 4) The selection process is carried out to extract the idealized model. The selection result is usually very 'dirty' as it contains many redundant entities. A purging operation to de-select these unnecessary entities is offered in the prototype system.

(Step 5) Perform further CAE pre-processing tasks (such as automated mesh generation) on this model, or directly transfer this model to the CAE systems.

No	Feature Name	Creation Order	Bool	Appl. Domain	Primitive	Effective Primitive	LOD/LOA Model
1	Disk	0	+	A	$P_{0,1}$	$P_{0,1}$	$P_{0,1}$
5	Boss	2	+	A	$P_{2,1}$	$P_{2,1}$	$P_{0,1}+P_{2,1}$

Tab. 3 Reordered idealization features for the example solid model in Fig. 4.

5.3.2. Criteria of Level of Abstraction (LOA)

The criteria of LOA are application-dependent. In structural analysis, the aspect ratio is a good criterion to determine the abstraction level [1, 2]. For instance, a solid object is abstracted to a beam element if two of the orthogonal dimensions are at least several times smaller than the third dimension, which is the length of the beam. A solid object is abstracted to a plate or a shell element if one dimension, the thickness, is at least several times smaller than the other two dimensions. A beam element is represented by a wireframe model, while a plate or a shell element is represented by a sheet model in our system.

In injection moulding simulations, the mesh size plays an important role in selecting an abstract model. 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 eliminated if its diameter is smaller than the mesh size.

Let us investigate the example case in Fig. 4. As shown in Fig.4, t_0 denotes the thickness of the base plate F_0, d_1 denotes the diameter of the holes F_1. The parameters t_2 and d_2 are the thickness and diameter, respectively, of the boss F_2, and x is the length of one lateral side of a mesh element for FEA. If the abstraction model selection function is implemented with the following conditional statements and $t_2 < t_0 < d_1 < d_2$, then the abstract models are changed as illustrated in Fig. 9(a) and the x value is increased. All of the abstract models for the combination of LODs and LOAs are presented in Fig. 9(b).

6. CASE STUDY

Fig. 10(a) describes the modelling process for a sample object that is a simplified model of the speed reduction casting introduced in [3]. The idealization feature table for LOA = 0 is shown in Fig. 10(b). Here, the criterion of LOD is the volume of the feature. This table shows the resulting order of feature arrangement, while Fig. 10(c) shows the results of the idealization process. The abstraction is applied to the Blade_Pattern feature first, and then the Hole_Pattern feature, and finally the Base feature.

7. ACKNOWLEDGEMENTS

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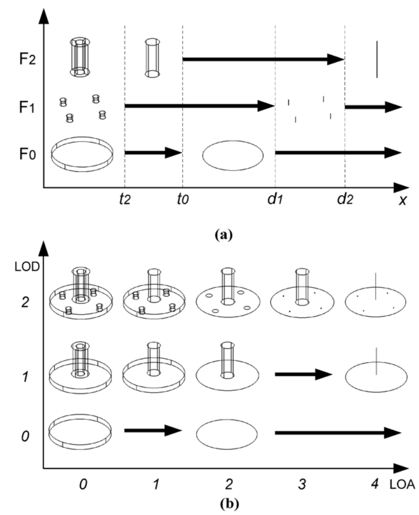

Fig. 9 Idealized models for the sample model in Fig. 4: (a) abstraction of features; (b) abstract models at various LODs and LOAs.

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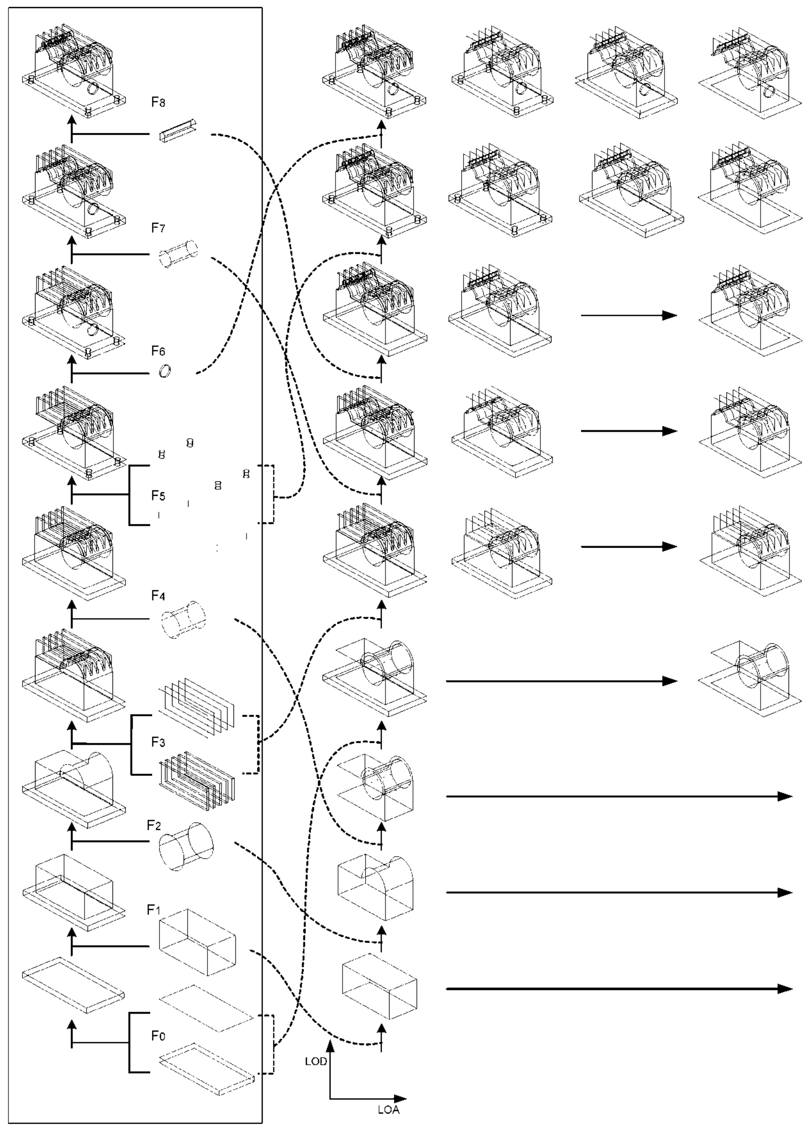
No	Feature Name	Creation Order	Bool	Appl. Domain	Primitive	Effective Primitive	LOD/LOA Model
0	Block	1	+	DA	P1	P1	P1
1	Cylinder	2	+	DA	P2	P2	P1+(P2)
2	Hole	9	-	DA	P4	P4	P1+(P2)-(P4)
3	Base	0	+	DA	P0	P0-P4	P1+(P2)-(P4)+(P0-P4)
4	Blade	3	+	DA	P3	P3-P4	P1+(P2)-(P4)+(P0-P4)+(P3-P4)
5	Bump	12	+	DA	P7	P7	P1+(P2)-(P4)+(P0-P4)+(P3-P4)+(P7)
6	Pad	13	+	DA	P8	P8	P1+(P2)-(P4)+(P0-P4)+(P3-P4)+(P7)+(P8)
7	Hole_Pattern	10	-	DA	P5	P5-P7-P8	P1+(P2)-(P4)+(P0-P4)+(P3-P4)+(P7)+(P8)-(P5-P7-P8)
8	Blind_Hole	11	-	DA	P6	P6-P7-P8	P1+(P2)-(P4)+(P0-P4)+(P3-P4)+(P7)+(P8)-(P5-P7-P8)-(P6-P7-P8)



(b) (a) (c)

Fig. 10 Idealized models for a speed reduction casting model: (a) modelling process for a sample speed reduction casting part; (b) the idealization feature table for LOA = 0; (c) the results of the idealization process.

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