INT. J. PROD. RES., 2002, VOL. 40, NO. 15, 3737–3750

Feature-based CAD-CAE integration model for injection-moulded product design

Y.-M. DENG†*, G. A. BRITTON†, Y. C. LAM‡, S. B. TOR‡ and Y. S. MA†

One prominent characteristic of product design for injection-moulded parts is that design and analysis (e.g. flow simulation) go hand in hand to ensure that the design is manufacturable by the injection-moulding process. Despite the wide use of CAD and CAE systems, the two processes are still not integrated. There is no generic, unified model that allows both design and analysis information to be specified. In this paper, a feature-based CAD-CAE integration model is proposed to tackle the problem. The model comprises a hierarchy of CAD-CAE features such as part, wall, hole, rib, boss and treatment. The features are defined by their attributes and behaviours. With this model, information relating to both design and analysis can be specified and modified. The specified information from the design process is used to activate relevant CAE analysis routines, thus supporting integration from the CAD to the CAE process. If any of the specified design constraints is not satisfied from the CAE results, the initial model can be modified and the CAE analysis executed again. Hence, the model also supports integration from the CAE to the CAD process. A design case illustrates the bidirectional integration process.

1. Introduction

There are a few prominent characteristics of injection-moulded product (plastic part) design, one of which is that design and analysis go hand in hand to ensure that the design can be manufactured by the injection-moulding process. For this reason, both CAD and CAE systems are now widely used in practice. Despite the great achievements of applying CAD and CAE technology in injection-moulding design, it is known that the two processes are not integrated (Gabbert and Wehner 1998, Kagan and Fischer 2000). Different models are used for design and analysis, namely a design model is used for the CAD modelling and an analysis model for the CAE analysis.

One implication of this is that designers cannot specify their design intents for CAE analysis using current CAD design models. For example, assume that a designer has created an initial design model (a solid geometric model) using a CAD package. For aesthetic or functional considerations, the designer may wish to assign no-go areas for weld lines, sink marks and vestige marks from gates. These types of design constraints must be entered manually during CAE data input, because current CAD models do not have the facility to allow the designer to specify

Revision received February 2002.
† CAD/CAM Laboratory, School of Mechanical and Production Engineering, Nanyang Technological University, Nanyang Avenue, Singapore 639798.
‡ Singapore–MIT Alliance Fellow.
* To whom correspondence should be addressed. e-mail: mymdeng@ntu.edu.sg

International Journal of Production Research ISSN 0020–7543 print/ISSN 1366–588X online
http://www.tandf.co.uk/journals
DOI: 10.1080/00207540210141643

this information (refer to the various commercial CAD systems). Hence, it cannot be passed to CAE analysis automatically. Lack of this information may result in the loss of design intent. The search space during CAE simulation and optimization is larger than need be, which in turn lowers the computational efficiency of the analysis.

On the other hand, if the designer tries to specify this information using a CAE analysis model, he or she may face some difficulties. This is because an analysis model is different from the design model. The geometry specified in the analysis model is often a simplified version of the geometry used in the CAD model, and they are often of different representations (B-Rep, CSG, etc.). The designer may have difficulty using a model he or she is not familiar with.

To tackle this problem, this paper proposes a feature-based CAD–CAE integration model that comprises a number of CAD–CAE features. Designers can specify their design intents relating to both design and analysis with the model, hence it can be used not only for design generation, but also to initiate CAE analysis directly and also to allow the designers to modify the model automatically according to the specified criteria.

Section 2 presents a brief literature review to clarify the scope of the research and to identify the limitations of existing works. Section 3 elaborates on the proposed CAD–CAE features, their attributes and behaviours. The integration model based on these features is discussed in Section 4. Section 5 presents a software prototype. By using this prototype, a design case is studied in Section 6 to illustrate how the model can be used to support both CAD to CAE and CAE to CAD integration. Section 7 summarizes this research and outlines the prospects for future work.

2. Literature review

Injection-moulding CAE analysis aims at deriving verification and evaluation information about plastic part mouldability, part manufacturing efficiency and cost, part quality in terms of residual stress, meld/weld lines, sink marks, etc. This has now become a very important aid for injection-moulded product design.

Earlier work on establishing links between design and analysis focused on the idealization of the CAD model for CAE analysis and automatic mesh generation. In fact, techniques for mesh generation have attracted considerable research effort for the past three decades, particularly with regard to automatic (or free) meshing schemes (Arabshahi *et al.* 1991, Francois *et al.* 1999). Work on model idealization includes techniques to support idealization and abstraction (Shephard and Finnigan 1988, Shephard *et al.* 1990, Belaziz *et al.* 2000), as well as geometric reasoning for enabling idealization and abstraction, such as mid-surface abstraction (Sheehy *et al.* 1995, Razayat 1996, Fischer and Wang 1997). Although model idealization still requires human interference because of its nature of subjectiveness, automatic mesh generation is now well established within various CAE applications. Almost all commercial CAE packages (and some CAD packages as well) provide such functionality.

However, model idealization and automatic mesh generation only support transformation from CAD model to CAE model in terms of geometry. The derived idealization model (either with or without mesh generation) still needs to be provided with information such as material type, manufacturing process or physical behavioural process, boundary conditions, etc. That is, the model still lacks information essential for CAE analysis.

A more complete research aims at integrating the two processes. There are, in general, two approaches for achieving CAD-CAE integration. One is through development of an integrated environment with built-in CAD and CAE functionality. For example, Kim (1985) developed an injection-moulding synthesis system that integrated both design synthesis and melt flow analysis. Irani *et al.* (1995) developed a framework for integrating CAE and iterative design/redesign of injection-moulding feed system. Kagan and Fischer (2000) developed an integrated mechanically based CAE system by using a B-spline finite-element model for both design and analysis stage. This system is a more integrated approach than the other systems because both the design and analysis use the same representation model—there is no need to transfer the design model to the analysis model. However, all these systems achieve CAD/CAE integration on condition that they are within an integrated computational environment. Obviously, this approach has its limitations, given the wide applications of those sophisticated standalone CAD and CAE packages at present time.

Another approach looks more promising: develop a unified model on top of existing computer-aided systems that incorporates both CAD design information and information needed for CAE analysis, and also provides tools for rapidly capturing and manipulating this information. This model is different from the various existing neutral files such as DXF and IGES, in that it incorporates product life cycle information rather than geometry alone. In other words, it requires adding functionality to existing CAD solid modellers to allow designers to specify and formalize non-geometric CAE information. In this respect, the STEP standard (ISO 10303) provides a promising model paradigm. It has several partial models concerning the finite-element analysis (FEA) method (part 104) and the CAD-FEA link (parts 209/214) (Gabbert and Wehner 1998). However, these partial models are still in draft status, and they are of limited application. For example, Part 104—the integrated application resource for finite-element systems—covers only static linear so far. To compensate for this drawback, Gabbert and Wehner (1998) proposed an object-oriented partial product model (OOPPM) for the integration of design and analysis. This idea, however, has not been elaborated nor implemented.

Feature-based design technology has been demonstrated as very effective in capturing non-geometric information in a geometric design model (Bronsvoort and Jansen 1993, De Martino *et al.* 1994, Shah and Mäntylä 1995, etc.). There are numerous feature-based design models that support incorporation of both geometric and non-geometric design information. However, the focus of current research in this respect is on design for manufacturing and integration of CAD and CAM processes (Yueh and Miller 1995, Kim and O'Grady 1996, Chen and Wei 1997, etc.). Hence, the non-geometric data are not oriented towards engineering analysis. One of the implications for using CAM-oriented features in CAE analysis is that it may lead to difficulty in attaching CAE-relevant data to the CAD design model. For example, an engineering analysis may need to associate a certain attribute with only partial CAM-oriented feature, such as the aesthetic constraints on the wall feature of a plastic part. Another example is the thickness attribute used in the CAE analysis. In a CAM-oriented feature ontology, only an extrusion feature has thickness information. However, this attribute is used by many more CAE-oriented features, such as rib feature and boss feature.

Arabshahi *et al.* (1993) attempted to incorporate analysis information in a design model. They proposed a scheme for automated CAD-FEA transformation. The scheme consisted of a robust and comprehensive product description system (PDS), a semi-automated means for transforming PDS data into an attributed, abstracted and (possibly) subdivided model ready for finite-element mesh generation, as well as some other features found in the general CAE environment. A set of tools were also suggested, such as an *attribute editor* to allow the users to attach attributes (material properties, analysis type, loads, constraints, etc.) to the features of the design solid model, a *detail editor* to allow the users partially to automate the abstraction and idealization of PDS data to form a suitable CAE analysis model, and a *dimensional reduction aid* to reduce the feature dimensions, thus to reduce the cost and complexity of the analysis. The paper, however, did not provide information about how the proposed PDS can be formalized, hence it is not clear how the different types of attributes (non-geometric data) are related with each other and how they are related to the geometric model itself.

To conclude, development of a unified design-analysis model based on existing CAD/CAE systems is a promising strategy for injection-moulding CAD-CAE integration. Current research has a number of limitations when applied to the injection-moulding domain. First, there is no formalized model to describe all aspects of the CAE-oriented design information. Second, although some feature-based design models can describe both geometric data and non-geometric design information, the non-geometric data are mainly oriented to manufacturing processes. These models are thus not suitable for engineering analysis. It is thus necessary to develop a CAE-oriented new feature ontology. Third, existing methodologies in developing analysis models do not provide facilities for representing the model processing operations, which are important in enabling automatic modification of CAD design model and automatic generation of CAE analysis model. There are only a few methodologies that support recording of operations (Shephard and Finnigan 1988, Arabshahi *et al.* 1993, etc.). However, without a formalism to represent these operations it is not possible to generalize them and hence extend their range of applicability.

3. CAD-CAE features

3.1. *CAD-CAE feature ontology*

Based on the findings from the literature review, the authors propose a novel feature ontology consisting of a number of CAD-CAE features. These features represent not only the geometric information of a plastic part, but also the design intents oriented to analysis.

- Part feature: contains the overall product information of a plastic part.
- Wall feature: forms the basis of a plastic part.
- Development feature: developed from the wall features, such as rib features, boss features, hole features, etc.
- Treatment feature: used as the treatment of other features, such as chamfer features, round features and fillet features. They are commonly used in conventional CAD/CAM systems. However, it is necessary for the designer to specify whether they can be suppressed during CAE analysis. Hence, they also contain analysis-related design intent information.
- Subwall/development feature: used to allow the designer to specify analysis-oriented information (mostly constraints) on a subarea of a wall feature or a development feature. The subarea could be a face, an edge, part of a face,

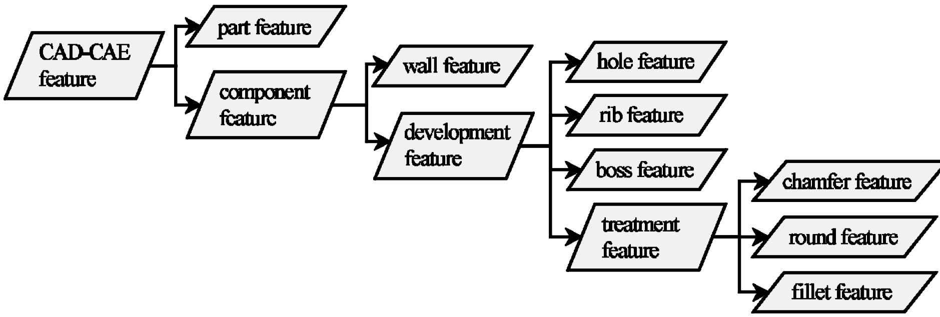

Figure 1. Types of the CAD–CAE features.

segment of an edge, or even a point on the corresponding feature. For example, the designer may wish to specify part of a wall face or segment of a wall edge to be no-go area of a gate location. For brevity, this feature is also referred to as a subfeature.

Wall feature and development feature are also called 'component features', because they are components of a plastic part. Figure 1 shows these different types of features.

Note that quite a few researchers have used wall, hole, boss, rib, etc. as design features for injection-moulded product design (Pratt *et al.* 1993, Al-Ashaab and Young 1995, Lee and Young 1998). The authors use similar set of features but adapt them to incorporate both CAD and CAE design information.

3.2. *Feature attributes*

3.2.1. *Specific attributes*

Each feature contains design and analysis related data, called feature attributes. The part feature contains attributes such as part identifier, thickness, material, constraints, analysis type and the relevant boundary condition and processing condition data (e.g. gate location for flow simulation, mould/melt/coolant temperature for cooling analysis, etc.). The thickness and material information will be inherited by component features of the part (wall features, rib features and boss features). These features can also be specified with different thickness if necessary. The constraints relating to a part feature define the criteria that the analysis results must achieve, e.g. the maximum shear stress must not exceed a certain value.

The wall feature has attributes such as wall identifier, geometry, thickness (in case the wall has a different thickness from the overall part thickness) and constraints. In this paper, constraints on a wall feature specifically refer to the gate location constraints, which act on the edges and surfaces of the wall geometry.

The hole, rib, boss and treatment features have similar attributes except that hole and treatment features do not have the thickness attribute. They all have an additional attribute: suppressibility. This attribute characterizes whether the feature can be suppressed when abstracting the analysis model (model idealization). Note that in this paper hole features include any general cutout features on the wall, rib and boss features. Similarly, boss features include any outstanding (protrusion) parts from the wall features.

The subfeatures have their corresponding geometry and constraint attributes.

3.2.2. *Common attributes: relationships between features*

Besides the above specific attributes, there is also relationship information that specifies how features can be combined to form the design model. The part feature has pointers to all the wall features. The wall feature has pointers to its subwall features, as well as pointers to its embedded development features. Since the parent of a wall feature is definitely the part feature, it is not necessary to capture this information as an attribute of the wall feature.

The hole, rib, boss and treatment features all have pointers to their parent features, where the rib and boss features only have the wall feature parents, while the hole features can have both the wall feature parents and rib/boss feature parents. The treatment features can have all the other features as their parent features.

In the reverse direction, the rib and boss features have pointers to their embedded hole features and treatment features, as well as pointers to their children subrib/boss features. The hole features only have pointers to their embedded treatment features. Figure 2 shows the specific feature attributes and the relationship attributes between the features.

3.3. *Feature behaviours*

Besides the attribute information, the features also have certain behaviours, that is, the operations of the features on their attributes. These include the interactions between the features and also the response of the features to the actions from the outside, including the designer.

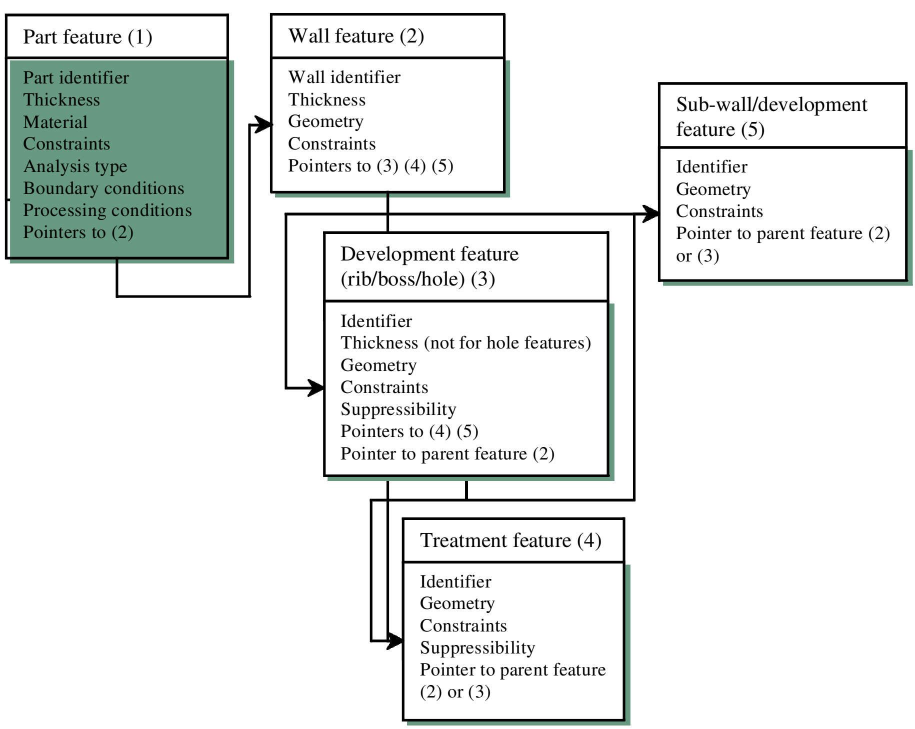

Figure 2. Attributes of the CAD–CAE features.

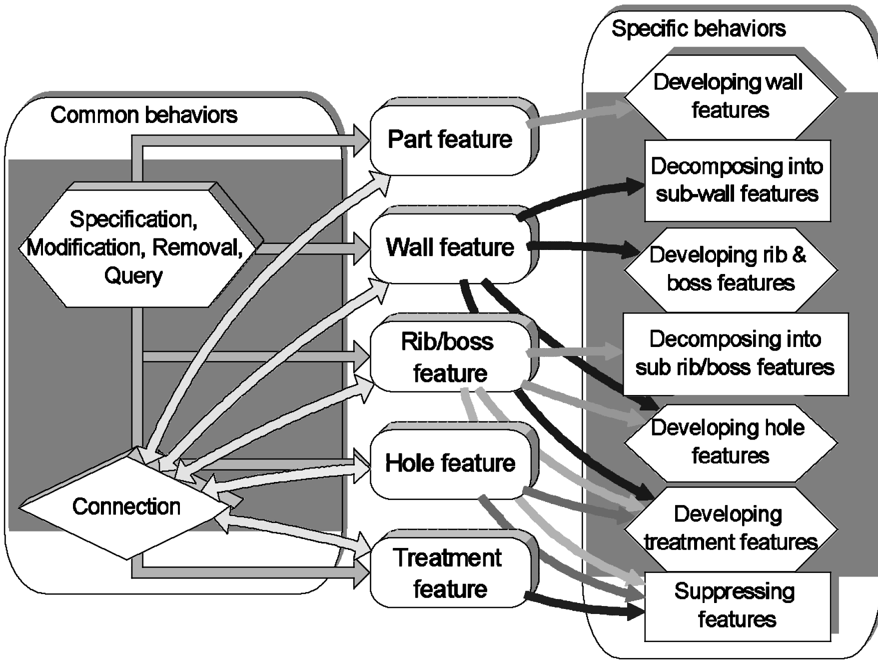

Figure 3. Behaviours (operations) of the CAD–CAE features.

Common feature behaviour includes specification, modification, removal and query of feature attributes (coming from designers), as well as connection operations between the features. See figure 3 for an illustration.

The specific behaviour of each feature is as follows. Part feature has a behaviour of developing wall features. This is used for generating wall features during the design process. Wall feature has a behaviour of developing rib/boss/hole/treatment features. It also has a behaviour of decomposition so that subwall features can be developed.

Rib/boss feature has a behaviour of developing hole features and treatment features, while hole feature has a behaviour of developing treatment features. All rib/boss/hole/treatment features have a behaviour of suppressing themselves. The designer can specify whether a rib/boss/hole/ treatment feature is suppressible via the corresponding attribute 'suppressibility'. If yes then such a behaviour can be activated during the analysis model abstraction process.

4. CAD-CAE integration model

The integration model is constructed from the defined CAD–CAE features. This includes constructing the geometry of a plastic part by Boolean operations, as well as establishing relationship information between the features. If a CAD system supports automatic Boolean operations during geometric feature creation, then only the second task is required.

The relationships between the CAD–CAE features form a hierarchical structure of the integration model. At the top of the hierarchy is the part feature. The second level consists of a number of wall features. Development features and treatment features are at the next level of the hierarchy. The lowest level includes subfeatures.

Following the relationships between the features the hierarchical model can be easily constructed. The designer or a predefined routine (this has been implemented in the prototype system to be discussed below) can check the part feature to get all wall features. Each wall feature is then examined to get its embedded development features and treatment features, if any. The process is continued until all features are retrieved and constructed.

After the creation of the integration model, an analysis model is automatically abstracted for the desired CAE analysis. The abstraction process involves abstracting an idealized geometric model (idealization) and abstracting non-geometric analysis information, such as material type, boundary conditions, processing conditions and constraint information. The idealization involves simplifying the geometric model to suppress non-significant features (suppressible features). Since the CAD–CAE features contain information about suppressibility, idealization is achieved easily.

Note that although the process requires an analysis model, the model is *abstracted* from an integration model, not converted from CAD geometric model as is current practice. The major difference between these two approaches is that with the proposed model all the information is available for CAE analysis and hence CAE analysis can be initiated without further interaction from the designer; while conversion from CAD geometric model only provides geometric information for analysis, hence the model is incomplete.

With all the information available from model abstraction, the underlying CAE system can be activated to conduct the intended CAE analysis. As such, integration from CAD to CAE process is implemented. The analysis results are then examined to check whether any of the predefined criteria—which are in the form of part feature constraints in the integration model—is violated. If any criteria is violated then the process will go back to the design stage, where CAD-CAE features are modified. Both the CAD geometry and the CAE-related data in the integration model can be modified. Hence, it supports integration from CAE to CAD process as well. After modification, a new integration model will be constructed and analysis model abstracted, so that another CAE analysis can be activated. The process iterates until all criteria have been satisfied.

5. Software prototype

Based on the proposed integration model, the authors have developed a prototype system for injection-moulding design. The system consists of a number of modules: CAD platform module, CAE platform module, feature creation and modification module, plastic material library module, feature prototype library module, integration model construction module, analysis model abstraction module, and analysis activation and results processing module. A graphic user interface provides tools for the designer to interact with these modules, which will be elaborated in the following. Figure 4 shows such a system framework.

In the implemented software prototype, Solid Edge® is used as the CAD platform, while Moldflow® is used as the CAE platform. Because Solid Edge supports ActiveX automation, the functionality of this system can be easily accessed by the outside programs. Figure 5 shows the GUI of the developed prototype system. The upper panel shows the system menus and tool bars and the lower-left panel shows the feature tree of the plastic part being designed. The underlying Solid Edge system is shown in the lower-right corner. During the feature geometric modelling

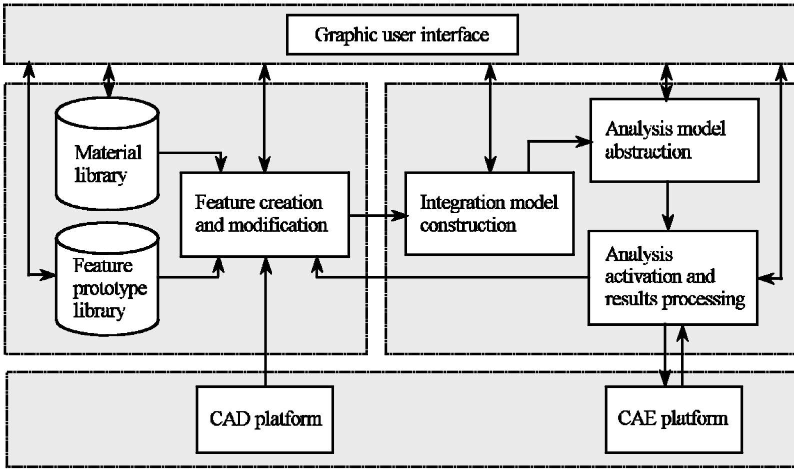

Figure 4. Framework of the software prototype.

process, the designer uses the GUI of the CAD system. Otherwise, the GUI tools provided by the prototype system are used. For feature manipulation, including creation, modification, query, and so on, the designer can use system menus and tools bars or popup menus under the feature tree window. For other tasks, like model construction, analysis model abstraction and CAE analysis activation, only system menus and toolbars are applicable.

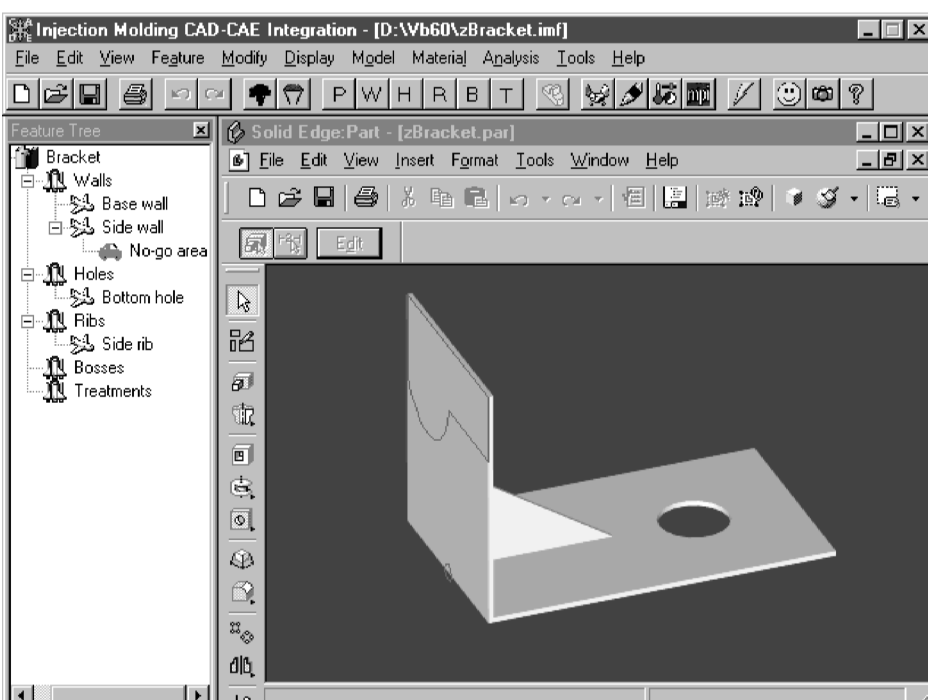

Figure 5. Graphical user interface of the developed prototype system.

Once the CAD geometry has been created CAD-CAE features can be created by assigning CAD geometry to them. The system will automatically access the CAD system and allow the designer to select the desired geometry for each CAD-CAE feature from the CAD environment. Interactive feature definition is used for the same reason it is used for CAM-features: a CAD geometry feature may not exactly contain the geometry and information required for the CAD-CAE feature.

Other information relating to the CAD-CAE feature can also be specified. For example, if a designer is creating a hole feature, he or she can use the provided user interface to specify whether the hole feature can be suppressed during the analysis model abstraction process. One or more gate locations are specified as the boundary condition for flow simulation. For example, in figure 5 a gate location marker is created using a circle. The system also has a built-in material library containing material information such as material type, manufacturer name and trade name. This information serves as an index to the material properties database within Moldflow environment. The designer can specify this information by browsing through the material library.

After creation and specification of all CAD-CAE features, the system will automatically construct the integration model. The designer can then activate the relevant CAE analyses directly using this model. This includes the automatic abstraction of analysis model, generation of mesh model, and execution of Moldflow routines. Once the mesh model has been generated, the non-geometric analysis information incorporated in the integration model is abstracted and tailored for the intended analysis. For example, the gate location information in the integration model corresponds to the gate location marker geometry (which is a circle in figure 5). The system will extract from the model the 3D coordinates of the gate location (e.g. centre of the circle) and then examine all the coordinates of the nodes from the generated mesh model to determine the corresponding node. Under the Moldflow environment, the corresponding node number is used to create a boundary condition file.

Similarly, other information is also abstracted and processed, which, together with the generated mesh model and boundary condition file, is used to create the so-called Moldflow inputs file. This file contains all information necessary for activating CAE analysis, either directly or through file names as pointers. As such, the intended CAE analysis can be executed automatically.

6. Design case study

A plastic part design case is studied to indicate the proposed integration model and its application in enabling integration from CAD to CAE process and vice versa. This is an L-shape bracket shown in figure 5. By using the predefined features from the prototype system, the designer first creates a part feature that contains the overall information of the plastic part being designed.

- Part identifier: Bracket.
- Thickness: 1.5 mm.
- Material:
    - Type: PP.
    - Manufacturer: Amco Polymers, Inc. [AMOCO].
    - Trade name: 10-1246 [AM800].
- Analysis type: Filling analysis.

- Boundary condition: the gate location marker is shown in figure 5.
- Processing condition:
  - Melt temperature: 235°C.
  - Mould temperature: 40°C.
  - Injection time: 2 s.
- Constraint: Maximum bulk shear stress < 0.25 MPa (this is the maximum allowed value for the specified material).

Here the gate location is determined by the designer by considering both design requirement and the requirement of injection-moulding process.

Next, two wall features are created: 'Base wall' and 'Side wall'. The attributes of the first wall feature are listed below:

- Wall identifier: Base wall.
- Thickness: 1.5 mm (this is inherited from part feature).
- Wall geometry: this is shown in figure 5.
- Constraint: it is allowed to put gate location on the top and bottom surfaces.

Assume that the designer wishes to specify that part of the outer surface of the 'Side wall' feature is not allowed to have gate location mark. A subwall feature is thus created:

- Subwall identifier: No-go area.
- Subwall geometry: this is shown in figure 5.
- Constraint: it is not allowed to put gate location here.

Note that the above features also have pointer information, for example, the 'No-go area' is a subfeature attached to the 'Side wall' feature.

After wall features, all development features are created, including a rib feature called 'Side rib' on the 'Base wall' feature and 'Side wall' feature, as well as a hole feature called 'Bottom hole' on the 'Base wall' feature. For brevity, their attributes are not listed.

With all the features created and their relevant information (geometric and non-geometric) specified, an integration model is constructed. By a single button click, the system will automatically carry out a series of operations, which eventually lead to the relevant Moldflow analysis routines be executed. Figure 6 shows two analysis results: bulk shear stress and fill time.

From the analysis result, the system will extract the value of the maximum bulk shear stress, which is 0.3272 MPa. This shows that the specified part feature constraint is violated: the maximum shear stress is greater than the maximum allowed for the specified material (0.25 MPa). Hence, the designer needs to modify the initial integration model to try to satisfy this constraint. He or she can either change the material used, modify the processing condition or boundary condition, or change the part geometry.

To demonstrate that the proposed model supports integration from CAE to CAD process, let us assume that the designer decides to change the part thickness. With the predefined tools from the system, the designer can specify which feature thickness (i.e. 'Base wall', 'Side wall' or 'Side rib') is to be modified, or rather to change the thickness of them all (i.e. the thickness of the part feature). The designer should also specify the step value, with plus value to increase the thickness, and minus value to decrease the thickness. The system will then automatically modify the

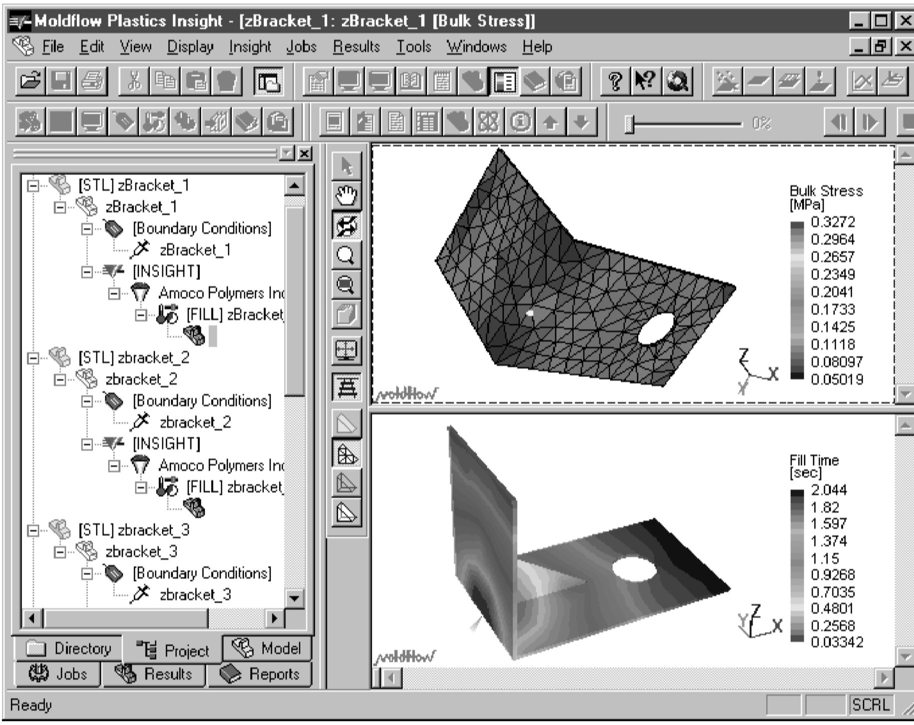

Figure 6. CAE analysis results: bulk shear stress and fill time.

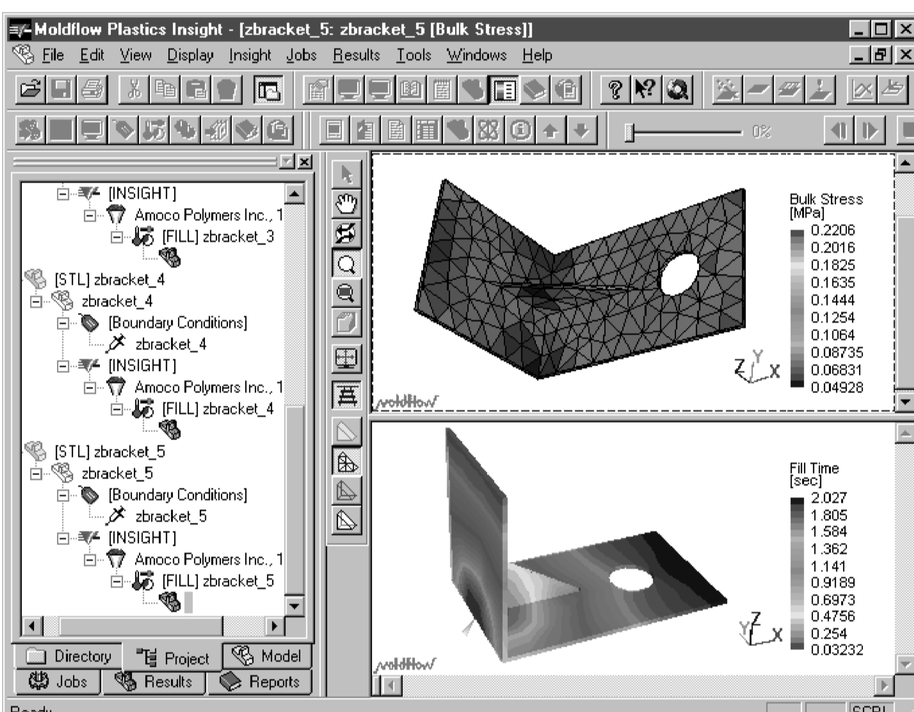

Figure 7. CAE analysis results after satisfying design constraint.

Analysis result name	Part thickness (mm)	maximum bulk shear stress (MPa)	Constraint satisfied?
zBracket_1	1.5	0.3272	no
zBracket_2	1.6	0.2965	no
zBracket_3	1.7	0.2877	no
zBracket_4	1.8	0.2628	no
zBracket_5	1.9	0.2206	yes

Table 1. Part thickness and maximum bulk shear stress.

integration model (including both the CAD geometry and other relevant information), and execute CAE analysis. The iterative process is carried on until the part feature constraint is satisfied. For this case study, a step value of 0.1 mm is specified for the thickness of the whole plastic part. In total five counts of iterations are used before the constraint is satisfied. That is to say, the part thickness changed from the initial 1.5 to 1.9 mm. Table 1 lists the results from these iterations.

Figure 7 shows the new analysis results after satisfying the specified design constraint. (For better illustration, different perspectives are used.) It is intuitively seen that part thickness has been increased while maximum bulk shear stress has been reduced. Note that other analysis results also changed, e.g. the actual injection time has changed from the original 2.044 to 2.027 s. Hence, in practice, a number of design constraints might be necessary to ensure a feasible design.

7. Conclusions

The paper has described and explained a feature-based CAD–CAE integration model for injection-moulded product design. The model is based on a new feature ontology oriented to CAD–CAE integration, called the CAD–CAE feature, which contains not only feature geometry, but also the non-geometric information required for CAE analysis. A number of CAD–CAE features have been defined, including their attributes (both geometric and non-geometric information) and behaviours, such as new feature creation, feature manipulation, feature decomposition, etc.

The research has shown that by developing an integration model, both design and analysis processes share a unified model. The designer can specify his or her design intents, such as design constraints, over the CAD–CAE features. The analysis related information is also specified over and attached to the CAD–CAE features. The features are then used to construct the integration model, which is subsequently used to abstract the analysis model for the CAE system and to execute CAE analysis. Hence, the proposed model enables transferring of non-geometric information from CAD to CAE process. The case study has demonstrated that the integration model can be modified automatically once an analysis result violates any of the specified constraints. An iterative process can be carried out until the constraint is satisfied. Hence, the model also enables integration from CAE to CAD process.

Future research is aimed at enriching the CAD–CAE features and model operation sets. Strategies for devising self-configurable CAD–CAE features so that they can be tailored for the specific application environments will also be investigated.

Acknowledgements

The project was supported by the Academic Research Fund, Ministry of Education, Singapore and Moldflow Pty Ltd.

References

Al-Ashaab, A. H. S. and Young, R. I. M., 1995, Design for injection moulding in a manufacturing model environment. *Journal of Design and Manufacturing,* **5**, 45–54.

Arabshahi, S., Barton, D. C. and Shaw, N. K., 1991, Towards integrated design and analysis. *Finite Elements in Analysis and Design,* **9**, 271–293.

Arabshahi, S., Barton, D. C. and Shaw, N. K., 1993, Steps towards CAD-FEA integration. *Engineering with Computers,* **9**, 17–26.

Belaziz, M., Bouras, A. and Brun, J. M., 2000, Morphological analysis for product design. *Computer-Aided Design,* **32**, 377–388.

Bronsvoort, W. F. and Jansen, F. W., 1993, Feature modelling and conversion—key concepts to concurrent engineering. *Computers in Industry*, **21**, 61–86.

Chen, Y.-M. and Wei, C.-L., 1997, Computer-aided feature-based design for net shape manufacturing. *Computer Integrated Manufacturing Systems*, **10**, 147–164.

De Martino, T., Falcidieno, B., Giannini, F., Hassinger, S. and Ovtcharova, J., 1994, Feature-based modelling by integrating design and recognition approaches. *Computer-Aided Design*, **26**, 646–653.

Fischer, A. and Wang, K. K., 1997, A method for extracting and thickening a mid-surface of a 3D thin object represented in NURBS. *Journal of Manufacturing Science and Engineering, Transactions of the ASME,* **119**, 706–712.

Francois, V., Cuilliere, J. C. and Gueury, M., 1999, Automatic meshing and remeshing in the simultaneous engineering context. *Research in Engineering Design,* **11**, 55–66.

Gabbert, U. and Wehner, P., 1998, The product data model as a pool for CAD-FEA data. *Engineering with Computers,* **14**, 115–122.

Irani, R. K., Kim, B. H. and Dixon, J. R., 1995, Towards automated design of the feed system of injection molds by integrating CAE, iterative redesign and features. *Journal of Engineering for Industry,* **117**, 72–77.

Kagan, P. and Fischer, A., 2000, Integrated mechanically based CAE system using B-spline finite elements. *Computer-Aided design,* **32**, 539–552.

Kim, C. and O'Grady, P. J., 1996, A representation formalism for feature-based design. *Computer-Aided Design,* **28**, 451–460.

Kim, S.-G., 1985, Knowledge based synthesis system for injection moulding. PhD thesis, Massachusetts Institute of Technology.

Lee, R. J. V. and Young, R. I. M., 1998, Information supported design for manufacture of injection-moulded rotational products. *International Journal of Production Research,* **36**, 3347–3366.

Pratt, S. D., Sivakumar, M. and Manoochehri, S., 1993, A knowledge-based engineering system for the design of injection moulded plastic parts. *Advances in Design Automation, ASME,* **65**, 287–295.

Razayat, M., 1996, Midsurface abstraction from 3D solid models: general theory and applications. *Computer-Aided Design,* **28**, 905–915.

Shah, J. J. and Mäntylä, M., 1995, *Parametric and Feature-based CAD/CAM: Concepts, Techniques, Applications* (New York: Wiley).

Sheehy, D. J., Armstrong, C. G. and Robinson, D. J., 1995, Computing the medial surface of a solid from a domain Delaunay triangulation. *Proceedings of the 3rd ACM Solid Modelling*, pp. 201–212.

Shephard, M. S. and Finnigan, P. M., 1988, Integration of geometric modelling and advanced finite element preprocessing, *Finite Elements in Analysis and Design,* **4**, 147–162.

Shephard, M. S., Korngold, E. V. and Wentorf, R., 1990, Design systems supporting engineering idealisations. In *Geometric Modelling for Product Engineering* (Amsterdam: North-Holland).

Yueh, Y.-S. and Miller, R. A., 1995, A systematic approach to support design for manufacturability in injection moulding and die casting. *Proceedings of the Computers in Engineering Conference and the Engineering Database Symposium,* ASME, pp. 755–765.