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A Feature-Based Engineering Methodology for Cyclic Modeling and Analysis Processes in Plastic Product Development

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ABSTRACT

Developing a high quality plastic part must cyclically check against required product functionality, structural stability, moldability, and cost effectiveness. Information modeling and managing associations among multiple engineering aspects is essential to maintain engineering consistency. A feature-based methodology is introduced here to facilitate cyclic processes involved in product development. The methodology starts with building product specification model based on specification features that enable capturing design intention and common product information at the onset of new product development. New feature types are introduced for information modeling of related engineering aspects. Then the methodology is elaborated with an example for iterative design evolvement through feature modifications based on CAE analyses.

Keywords: feature-based, cyclic modeling, performance analysis, injection molding.

1. INTRODUCTION

Due to globalization and rapid technological changes, modern enterprises are challenged for developing high quality products with innovative features at lowest cost in shortest time-to-market. Therefore product design and development methodologies become more important than ever for companies to gain competitive advantages in marketplace. Generally, the development of a product undergoes several phases in its lifecycle including customer requirements analysis, conceptual design, detail design, structural analysis, manufacturability checking, process planning, manufacturing, quality inspection and so on [18,21]. Various engineering aspects are supported with separate commercial computer aided tools such as computer aided design (CAD), engineering (CAE), process planning (CAPP), manufacturing (CAM), inspection (CAI) etc. It is the expectation that with those tools, designers and engineers can carry out different engineering activities efficiently for the realization of the end product [25]. The reality is that many of these engineering aspects are inter-related and mutually constraining. Some parameters from an earlier stage may be used as input parameters for generating product model in a later stage. If any modification is introduced based on any one aspect, such as product performance assessment, the inter-dependent product models need to be updated to ensure engineering principle and design consideration consistency across all engineering aspects [12,13]. The iterative design-analysis-redesign cycles among engineering aspects hence become unavoidable during product development process in a concurrent and collaborative environment.

Injection molding parts are increasingly used due to the material performance-cost advantages with automated net-shape manufacturing process and relatively complex geometries. However, designing plastic parts is a complex and tedious job involving many modeling and analysis cycles for counting considerations from other downstream product engineering aspects. It is imperative to coherently check the designed part meets functional requirements, strength criteria under different loading scenarios, moldability concerns, and cost effectiveness [15]. Therefore, information modeling for associations among related engineering aspects is essential to maintain product information consistency in the cyclic design evolvement. A literature survey (described in section 2) carried out in this regard reveals that although many researchers have done considerable works in product information sharing and integration, in-depth research is still required for product performance-based design enhancement,

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capturing multi-facet engineering intents in the design process, and associating information across software applications.

This research work is focused to developing a feature-based product engineering methodology in order to facilitate cyclic processes involved among engineering aspects during the development of an injection molding plastic product. The methodology starts with building product specification model based on specification feature that enables capturing design intentions and common product information at the onset of new product development. Then the emphasis is on feature-based associative information modeling of the iterative process and design enhancement modifications based on product performance assessment.

The following sections are organized as follows. Section 2 discusses related research works carried out in cyclic design and analysis processes in product development. The framework of the proposed feature-based methodology and its components for cyclic design evolvement based on functional and structural requirements evaluation has been described in section 3. Section 4 illustrates the methodology for design enhancement through structural feature modifications based on performance analysis with an industrial case study. Section 5 enumerates conclusions and future research works to be carried out in cyclic process modeling for more automated information flow among engineering aspects.

2. RELATED WORKS

Cyclic design processes for injection molding plastic part involve collective considerations among multiple engineering aspects such as CAD modeling, structural analysis, molding simulation, and cost estimation. Taking into account the effects of downstream product aspects early in design stage helps reduce the number of costly design changes at later stages [18]. It is important to recognize that the ease of part manufacturability, structural stability, tooling requirements and product cost will eventually be determined by design of the product [15]. Therefore, product and process information sharing and integration among engineering aspects in the cyclic design processes are essential for product models consistency and minimizing costly design changes.

Many research efforts have been made to share and exchange product and process information among different application models to enhance the integration among product engineering tools. Such research efforts in engineering informatics can be categorized as four approaches, i.e. using neutral-format data for file exchange, developing integrated product development environments, meta-data based product engineering modeling, and multi-facet feature-based engineering integration. Using neutral standard formats such as IGES, STEP, DXF, and SAT for representing product data have been developed to overcome the issue of data interoperability among heterogeneous CAx systems [16]. However, transferring product model data back and forth among separate CAD modeling and analysis systems becomes a tedious and time-consuming process of modifying design model, idealizing, re-meshing and reapplying boundary conditions in cyclic design-analysis process [9]. More seriously, this approach lacks of robustness of engineering consistency by causing information loss during data translation processes and generates poorly-defined geometric entities due to the differences of modeling tolerances among geometric modelers [7].

An integrated environment for product development accommodates geometric modeling, engineering analyses and/or other modeling capabilities and eliminates the compatibility issue of geometry modeling kernel [23]. Therefore, researches have been focused on working with native CAD geometries for the creation of CAE meshed model [5]. An early idea on CAD-FEA integration was proposed by Arabshahi et al. [1] where he emphasized for automation of CAD-FEA transformation and FEA model preparation activities. Shephard et al. [19] proposed a simulation-based design approach which has four technical components that integrates existing CAD and CAE tools by enhancing simulation data management and adaptive improvement of simulation model. Lee [10] described CAD/CAE-integrated approach using multi-resolution and multi-abstraction modeling that creates a single master model containing all of the geometric models required for both CAD and CAE. Smit et al. discussed the idea of multiple-view feature modeling approach for creating and associating analysis view along with other product views [20]. Hamri et al. proposed a new shape representation technique called mixed shape representation that supports both B-Rep and polyhedral representation for creating CAD and CAE models [7]. Nowadays, almost all of the current major commercial CAx software packages such as Siemens NX, CATIA, Pro/E, and SolidWorks are being developed along this direction. Although integrated packages can host different engineering modules together, the integration is achieved primarily on lower-level geometric entities. Higher-level feature information is still missed in the process of transforming a CAD model into the corresponding CAE model. Besides, since analyst has different views of the same product model than designer, he needs to modify a lot of the designer's model to prepare it for the analysis purpose.

In order to support different product lifecycle aspects with commonly shared high-level information, researches on meta-data product information modeling for engineering processes have been conducted. The goal is to develop a base information model that facilitates achieving integration of design, analysis and other engineering activities at information level. In the past decade, product data management (PDM) systems are developed to cluster engineering files for different product development phases, projects, configurations, and relevant dependencies at meta-attributes level [11], but they do not solve data level integration issues. The researchers at national institute of standards and technology (NIST) [4] have developed a base-level product model, known as core product model (CPM), that is generic, simple, open, non-proprietary, extensible, and independent of any specific product development process. CPM is reported to be capable of capturing engineering context commonly shared in product development activities. CPM has further extended and many researchers have based their works on CPM. Further, Sudarsan et al. [21] proposed a product information modeling framework to support the full range of product lifecycle management (PLM) information needs. Within the framework, it also defines a design-analysis integration model as part of the PLM concept. Product engineering information model enhances product information consistency among engineering aspects. However, it does not itself integrate separate engineering applications or enhance iterative design evolvement. To be more realistically feasible, Gujarathi et al. [6] developed a common data model (CDM) containing all required parametric information for both CAD modeling and CAE analysis for CAD/CAE parametric integration.

Although the concept of feature was initially associated to geometries of a part, its use has been expanded to other applications in different stages of product lifecycles due to its flexibility and extensibility [13]. Shah states that features represent engineering meaning of the geometry of a part or an assembly, or represent a carrier of product information that may aid design or communication between design and manufacturing or between other engineering tasks [17]. Vandenbrande defines features as regions or an object that are meaningful for a specific activity or application [22]. All of the above definitions relate features back to shape aspects of a product. Thus features have been used extensively for information modeling of many product engineering aspects such as functional design, detailed design, assembly design, process planning, and machining. Hoffmann et al. [8] proposed a three-level multi-view semantic model for product feature description for enhancing semantic integrity of feature information throughout product development. Since features carry non-geometric information along with geometric data, they are also being used for information modeling of new product engineering areas [2]. Feature-based technologies such as feature extraction, conversion or feature association enhances integrating product design stage with other downstream lifecycle stages. Many feature-based integration efforts have been reported [3,12,24]. Ma emphasizes on the generic feature definition based unified feature scheme for achieving feature-based interoperability among engineering applications [14]. Since feature serves as an information unit having engineering meaning, feature concepts can be expanded to model other application areas such as cost estimation etc and to exchange high-level engineering information along with geometric data across applications.

However, the reported research works have not thoroughly addressed cyclic modeling and analysis processes among multiple engineering aspects. Current research approaches do not support effectively capturing engineering intentions behind a product concept generation such as customer requirements, required functions, technical specifications, and performance criteria in the modeling environment. Design intentions and high-level product information, such as loading conditions, load amounts and analysis meta data, cannot be shared across applications. High-level feature information gets lost in the transformation process from design model to analysis model. Existing modeling and analysis tools are usually good at data processing and image generation. The application tools have limitations in evaluation of product performance. Therefore, in this work, a methodology has been proposed that can enhance the iterative product design process capturing high-level common product information as specification feature and making design improvement through structural feature modification for compliance to functional and strength requirements.

3. FEATURE-BASED CYCLIC MODELING AND ANALYSES FOR PRODUCT DEVELOPMENT

3.1. Framework of Proposed Feature-Based Engineering Methodology

The methodology starts with building product specification model that facilitates capturing design intentions and commonly shared product information such as customer requirements, required functions, technical specifications, engineering knowledge, performance criteria, and their relationships at the beginning of new product development. Information about design process, structural analysis, molding process and cost estimation necessary for injection molding product development is accumulated with separate product and process information files. Engineering features considering their types, attributes and relationships are identified by investigating and analyzing information stored in product and process information files. Feature-based information models for engineering aspects are then developed by creating feature hierarchy for each aspect. For example, design feature hierarchy is created to represent conceptual and detailed CAD model development, and CAE feature hierarchy for representing structural engineering analysis process. Feature instances are created by taking their parameter values from product and process data files for automated updating of product models if parameter values in the data files are modified. Fig. 1 outlines the framework of the proposed feature-based engineering methodology for cyclic modeling and analysis processes involving multiple engineering aspects.

CAD modeling of a product is progressively carried out to serve the required product functions captured from the product specification model. CAD models of the product serves as the master models and newly introduced features and product specification model are connected with it using API functions. Product performance based on the CAD models is then analyzed. For example, with our example

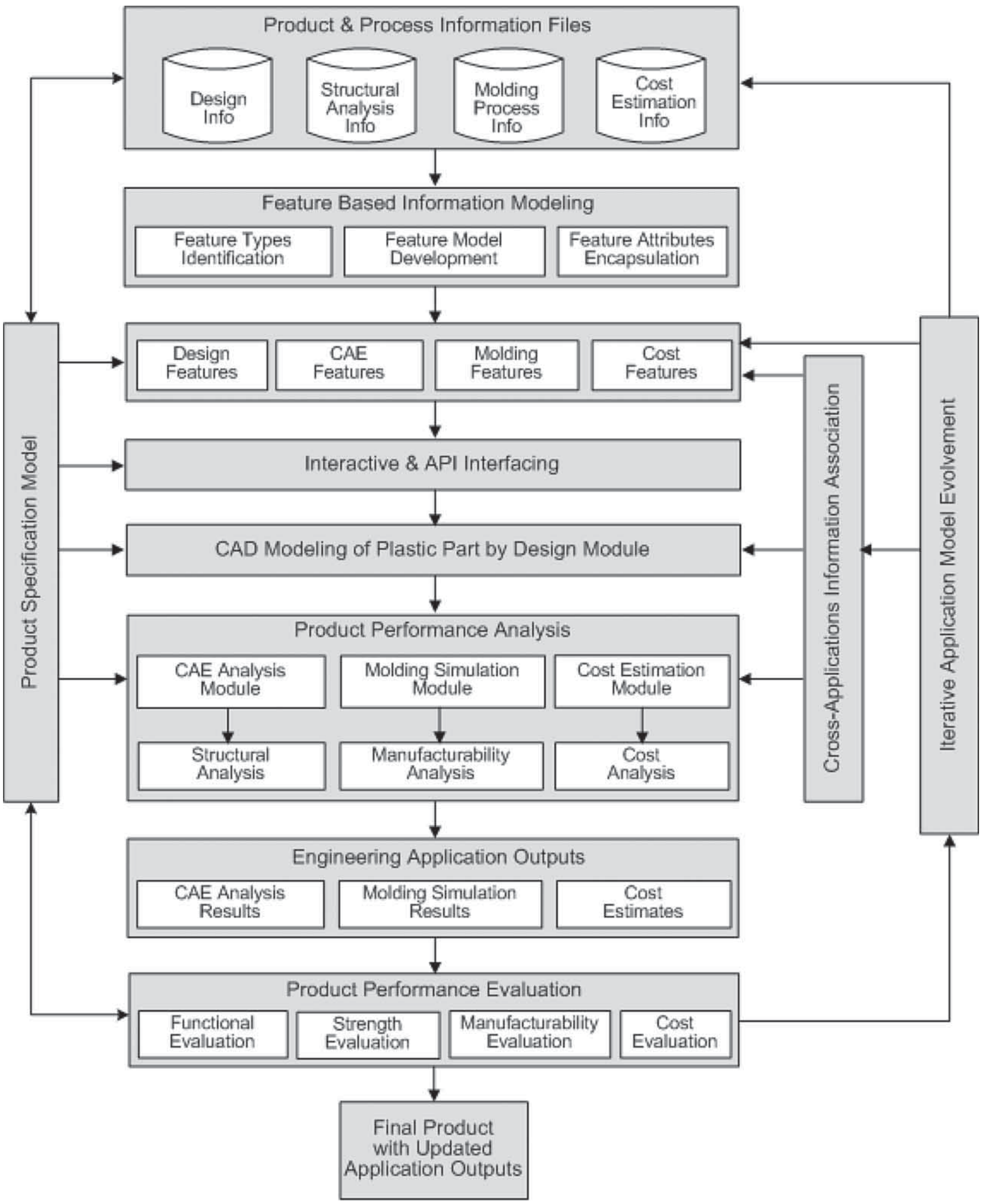
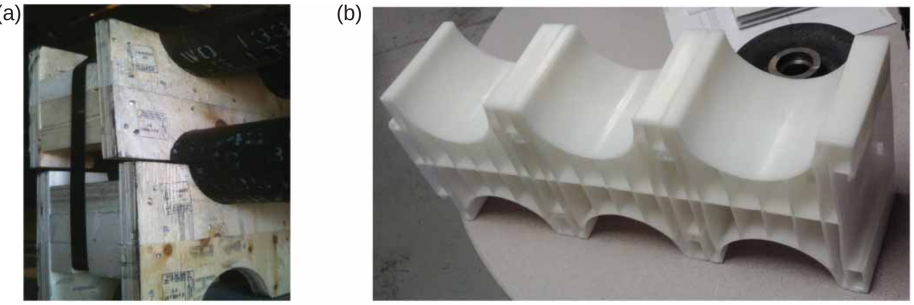


Fig. 1: Framework of feature-based engineering methodology for cyclic modeling and analyses.



(a) Original wooden support

(b) Preliminary replacement design

Fig. 2: An example plastic part design.

plastic part, i.e. an oil-drilling tube transport supporting piece as shown in Fig. 2, its structural rigidity, manufacturability and updated cost estimation are evaluated with different computer tools. The analysis results are assessed against predefined criteria for functionality, strength and moldability. Such criteria are managed by product performance evaluation process. Based on the evaluation feedback, CAD models or simulation models are modified iteratively through feature modifications. Existing feature attributes are then updated or new structural features are created for the iterative design enhancement. Information sharing and dependency relations among CAD model and analysis models are associated explicitly as cross-applications constraint relations. If any modification is done in inter-related engineering models, feature parameters would be updated accordingly to generate updated product engineering models. The detailed discussion on individual components of the framework is given in the following sections.

3.2. Product Specification Model

For a typical product series, the design specification structure can be generically abstracted into a common data structure with changing values of them for different instances. Such specification data can be formalized into software interpretable variables and shared among all of the engineering aspects for establishing engineering design criteria. Therefore, these specifications should be modeled as a common data file independent of any CAx system. Design evolvement and analysis evaluation results should be organized and directed towards fulfilling customer requirements and required functions through measureable product or part performance criteria. Generally, for many companies, such high-level specification variables are not captured at the onset of product development in a computer interpretable manner.

Therefore, a product specification model is proposed to capture all of the information gathered and created at product idea generation stage based on product specification feature. A specification model consists of a set of specification features. Fig. 3 illustrates the product specification feature semantic definition and its composition. The proposed specification feature data structure is defined as a *class* according to the object-oriented software engineering approach; it consists of other extended lower level features, such as those modeled for customer needs, application requirements, required functions, performance expectation, material requirement, and performance measures. For example, customer need features are mapped to capture the description of customer demands and preferences. Engineering knowledge is applied and implemented within the aforementioned features and the associated constraints. They could be specific in real world application to reflect the expert knowledge in the field, the best practice of the company, lessons learned from past cases, engineering calculations used in the product design, and relevant regulatory codes.

From customer needs and engineering knowledge, customer requirements are documented which are captured as customer requirements feature. Then required product functions are derived based on engineering knowledge and customer requirements and captured as function feature. Required functions are the pillars of the foundation for initializing conceptual product design. Conceptual design of a part should always check against the attributes of required function features to serve the product's intended use. All of different performance criteria for structural analysis, molding simulation and cost estimation are gathered as performance features so that the analysts know beforehand what the expectations and measures are, and what to achieve in the analysis process. Potentially, inter-feature constraints can be modeled and built into feature constraints to capture the intricate engineering dependencies. This proposed methodology emphasizes on capturing design intentions and specifications as early as possible; and the feature contents also serve as a common source of information and ensure information consistency across applications.

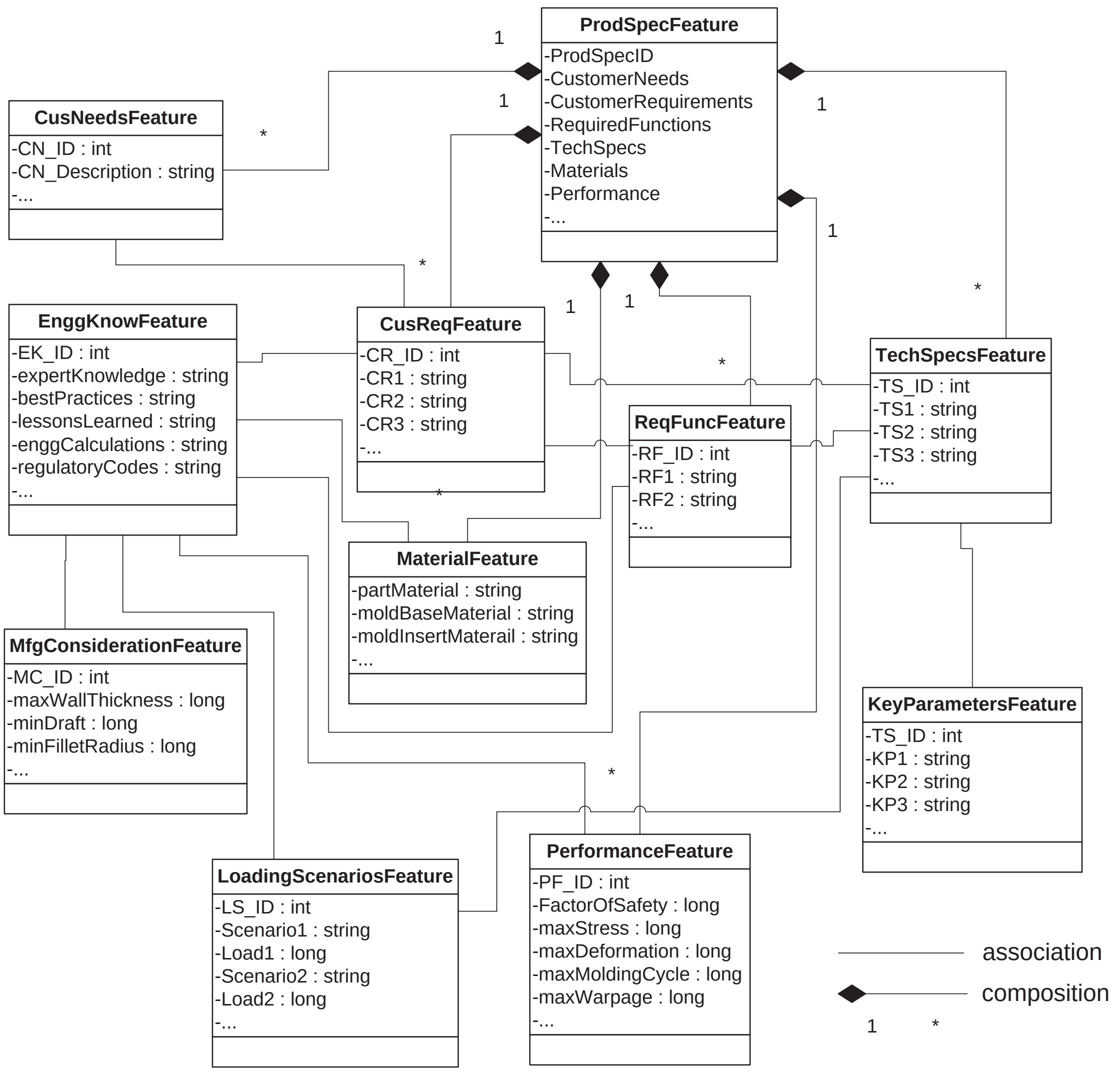


Fig. 3: Product specification model.

3.3. Feature-Based Information Modeling of Multiple Engineering Aspects

Features have the flexibility to capture both geometric and non-geometric engineering information characteristics for engineering modeling. This advantage can be once again demonstrated by introducing the necessary new feature types to encapsulate attributes and behaviors of related engineering consideration of different aspects such as structural analysis, molding simulation and cost estimation. Feature information related to product design, strength analysis, molding process and cost estimation can be organized in separate data storages. For example, the functional modeling method in CATIA has been used as a successful feature-based tool. In our preliminary research, separate feature data files are used. In the next paragraphs, from the feature modeling experience accumulated so far, some new feature types and their attributes have been identified for managing the cyclic plastic product design and analysis processes.

Fig. 4 shows a partial representation of feature-based information model of part design, CAE analysis, molding simulation and cost estimation. *Product Feature* acts as the top parent *class* and feature models of different engineering aspects are created with the *inheritance* relationship with the product feature. As a child class, *Product Specification Feature* is created to contain hierarchical technical specifications and key parameters related to both the set of customer requirement features and the set of design features. Design features have been classified as conceptual features and detailed design features. *Conceptual features* are those associative features created that reflect the function features in the specification model as discussed in the previous section. Such conceptual features are also linked to customer requirements

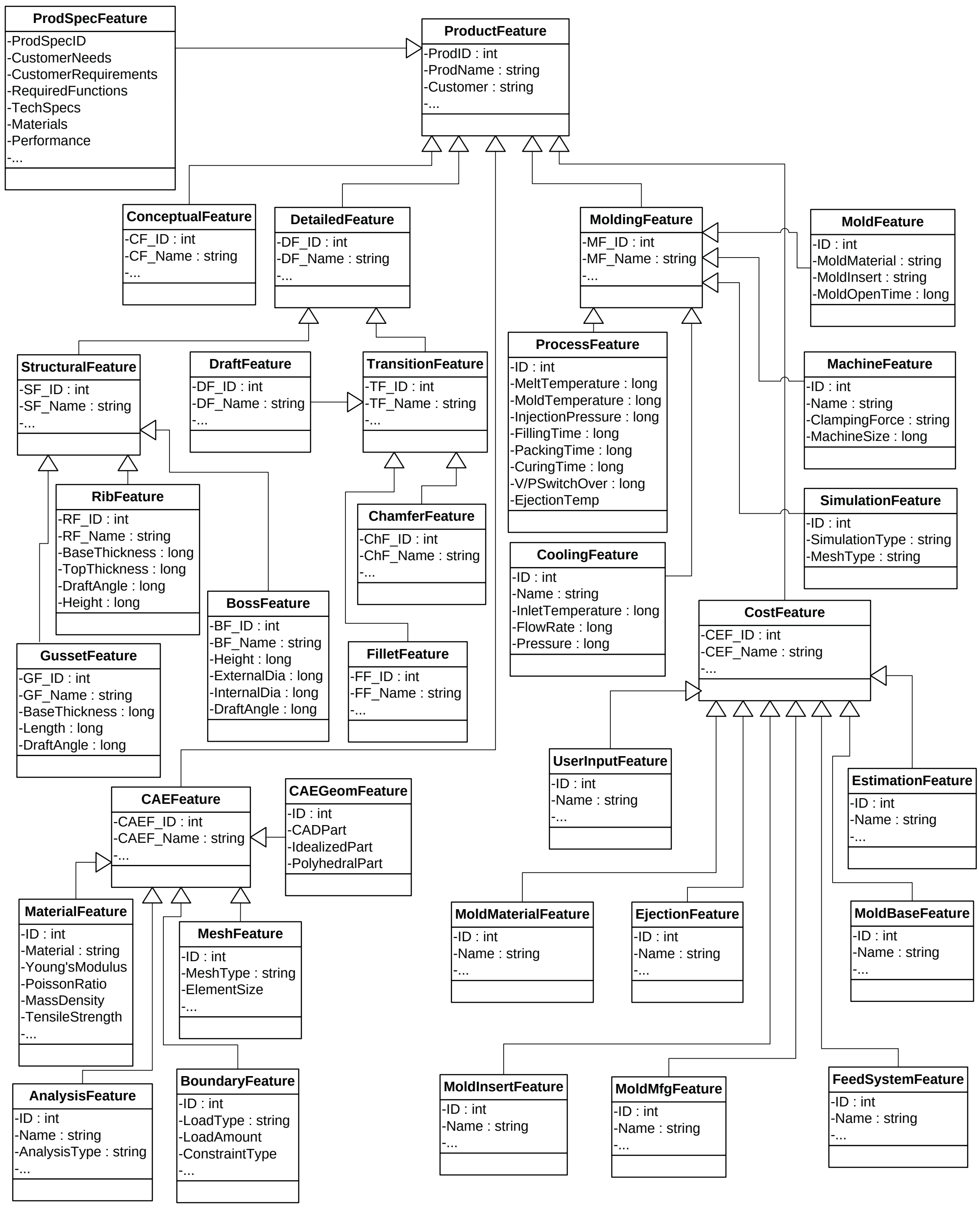


Fig. 4: Partial feature-based information modeling of multiple engineering aspects.

which are mapped to measure the customer satisfaction levels in product specification model. As shown in Fig. 2(a), the conceptual features give the hard-constrained outer shell for an injection molding part; the preliminary design is shown in Fig. 2(b). Then detailed design features are added progressively based on strength evaluation by CAE analysis. *Detailed features* are grouped into structural features and transition features. Structural features such as ribs, gussets and bosses are added for structural enforcement to the initial part shell of a plastic part. Transition features such as fillet, chamfer, draft etc are not introduced to the design model until the design becomes structurally strong enough to sustain loading conditions in different usage scenarios.

When structural analyses are carried out with CAE tools, e.g. Siemens NX Nastran for strength evaluation. The analysis information can be modeled as

CAE features such as CAE geometry feature, material feature, mesh feature, analysis feature and boundary feature. CAE geometry feature stores pointer to the CAD solid model, idealized part and polyhedral part which is suitable for carrying out CAE analysis. In order to plan for injection molding and the related simulation process, *molding features* such as molding process setup parameter feature, mold feature, injection machine feature, simulation feature and cooling feature have been created to represent necessary molding process details. Similarly, *cost feature* and its derived features can be created to represent different module costs, constraints, and their corresponding estimation and evaluation methods, e.g. those components involved in mold cost estimation process. Mold costing features include mold base, feed system, ejection system etc. They are created to enable modular mold cost estimation process. The data input for all feature parameters can be stored in spreadsheets and application models can be linked with spreadsheets using API functions for updating the models with the latest parameter values.

3.4. Product Performance Evaluation Method

As the designer modeling a product, he needs to evaluate the model against predefined performance criteria for its functionality, structural rigidity and moldability. Fig. 5 depicts the cyclic verification process of design models based on functional evaluation and strength analysis, and feedback loops for iterative design modifications. The performance criteria to be satisfied by a conceptual design are captured as performance features in product specification model and derived from customer requirements and engineering

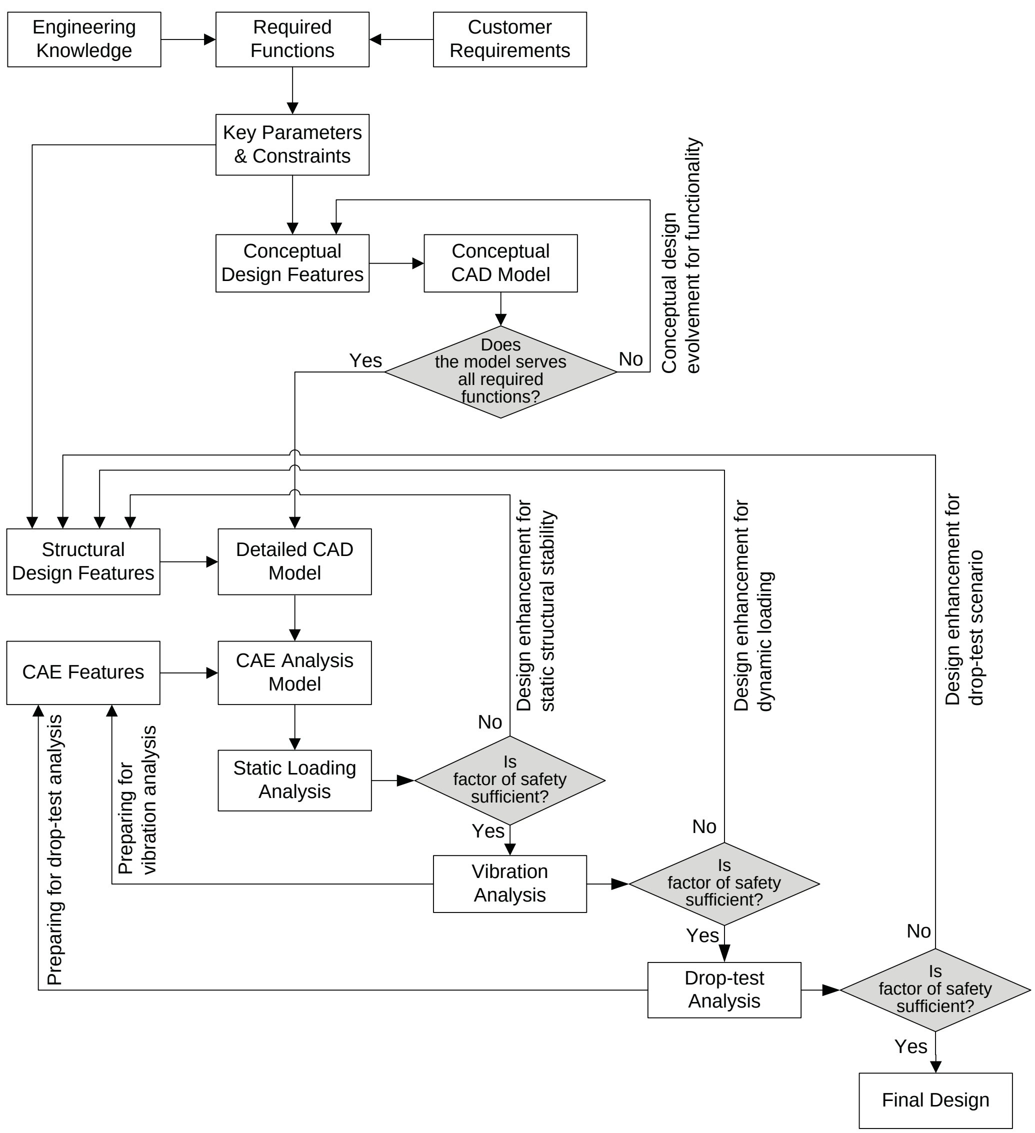


Fig. 5: Iterative design verification and modifications with functional and strength evaluations.

knowledge. The designer adds conceptual features to embody the required functions collectively in design model. When all of the required functions have been incorporated into the design, the conceptual part design is consolidated into a preliminary version.

With the completion of the conceptual design, the detailed design phase starts with more specific CAE analyses to verify different engineering constraints, such as the structural stability of the plastic part design in predefined loading scenarios which cover static loading conditions, dynamic vibration, dropping-test, etc. Usually, static loading conditions are checked first. The detailed design model needs to be prepared for CAE analyses. Capturing analysis information as CAE features as mentioned in section 3.3 helps reducing repetitive tasks of remeshing, reapplying boundary conditions etc. CAE analysis results are evaluated against predefined performance criteria, such as maximum stress, maximum deformation, and factor of safety, which are contained in performance features in the product specification model. If any performance criterion is not met, modifications for the design are warranted. For plastic part design, adding structural rib features is commonly practiced. Interactive trial and error for choosing right number of ribs as well as their patterns is necessary.

If the design exhibits sufficient strength under static loading, then vibrational loading conditions are checked. With the satisfactory results at this stage, the structural stability is then tested under drop-test scenarios. If a design possesses sufficient strength in all loading scenarios, then the design verification loop ends there and the design is finalized.

4. ITERATIVE DESIGN EVOLVEMENT THROUGH STRUCTURAL FEATURES - A CASE STUDY

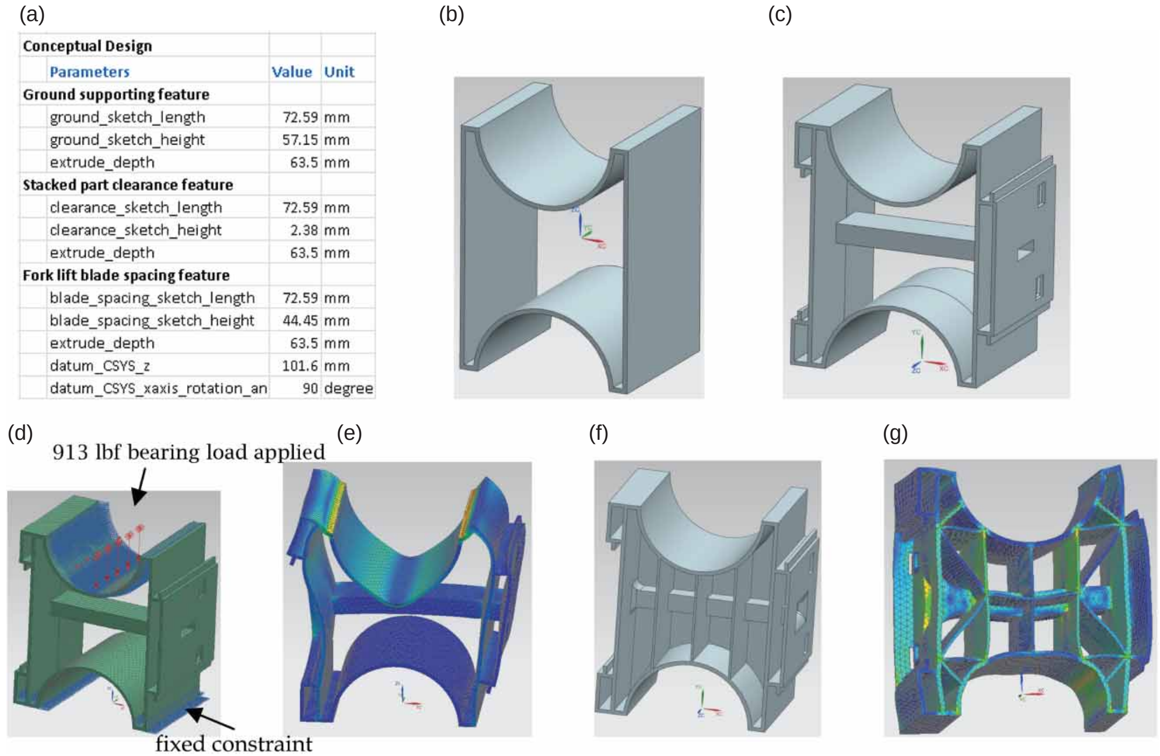
A case study for design evolvement through structural feature modifications based on CAE evaluation has been carried out for a plastic part which was intended to replace a traditional wooden support for transporting oil-drilling tubes as shown in Fig. 2 with HDPE. Tensile strength of HDPE used was 27 MPa and factor of safety (FoS) was chosen as 1.5 in all loading scenarios. With the company's preliminary design as shown in Fig. 2(b), the optimization of the design was required; because the material use was high (2.05 lb per part), and the vibration and dropping tests were not passed. FoS of the initial design in static loading, vibration and dropping were found to be 2.3, 1.3 and 1.1 respectively.

The product redevelopment process starts with capturing customer requirements, performance evaluation criteria, required product functions, technical specifications and key design parameters as specification features to construct product specification model. The attributes and their parameter values of the specification features, design features, CAE features, molding features and cost features have been captured in spreadsheet files in this conceptual stage of the research. Inter-dependent relationships among different features have been realized by embedding the relationships in spreadsheet cells. For example, technical specifications are dependent on customer requirements. If any parameter of customer requirements feature is changed, the corresponding parameters of technical specification feature will be automatically updated in the spreadsheet. On the other hand, design and analysis models are linked to their corresponding spreadsheets. The updating of product models is done manually by importing spreadsheets values from CAD/CAE environment. As the methodology will be implemented as a software prototype, API functions will be used to automate the updating process.

The feature-based information model serves as the guiding framework for the cyclic processes involved to derive the final satisfactory design. Since the design of a plastic part cannot be started with solid volume due to long cooling time and excessive material use, making the outer shell-like structure first and then adding structural features to reinforce the design is the best practice. Fig. 6(a) shows a partial view of conceptual design feature parameters which are linked to CAD model to realize the outer functional interfacing shell to match the tube profile shapes. The resulted model based on conceptual features is shown in Fig. 6(b). Next, the locking features and the inner hole for strapping the tube pile on a trailer are added as functional features in the conceptual design as shown in Fig. 6(c). The output is a hard-constrained outer shell of a plastic part. Obviously, the part design should possess enough strength to withstand industrial loading conditions. The design model is then analyzed for its structural stability under static loading, vibration and drop-test scenarios.

Therefore, the intermediate conceptual CAD model is checked by strength evaluation, i.e. FEA with NX Nastran. The static loading conditions are shown in Fig. 6(d), and the result is shown in Fig. 6(e). It does not meet the basic strength criteria. As the design evolves, different configurations of structural rib features are added semi-automatically and optimized according to FEA feedback to reinforce the design. Note that too much use of ribs increase material cost and hampers creating cooling channels in the mold. If a design possesses sufficient FoS under static loading scenario, it is then checked for vibrational loading conditions when transporting in a stack-up pile. If the design fails to meet predefined FoS, the detailed design is modified by varying the number and pattern of rib features.

One of the intermediate configurations is shown in Fig. 6(f) which uses vertical ribs. It satisfied static and vibrational loading requirements but failed in dropping test simulation. The locations of the highly stressed area in the part design were observed and different combinations of rib patterns were incorporated to the design to make it stronger.



Conceptual Design		
Parameters	Value	Unit
Ground supporting feature		
ground_sketch_length	72.59	mm
ground_sketch_height	57.15	mm
extrude_depth	63.5	mm
Stacked part clearance feature		
clearance_sketch_length	72.59	mm
clearance_sketch_height	2.38	mm
extrude_depth	63.5	mm
Fork lift blade spacing feature		
blade_spacing_sketch_length	72.59	mm
blade_spacing_sketch_height	44.45	mm
extrude_depth	63.5	mm
datum_CSYS_z	101.6	mm
datum_CSYS_xaxis_rotation_an	90	degree

Fig. 6: Iterative design model evolvement through structural feature modifications: (a) a partial view of conceptual design feature parameters; (b) the initial functional interfacing shell; (c) the intermediate conceptual part design; (d) the static loading conditions; (e) an intermediate static CAE analysis result; (f) a detailed design model; (g) final design satisfying all evaluations.

The final design is shown in Fig. 6(g) which uses combination of rib patterns and possesses a factor of safety higher than 1.5 in all loading conditions. Sets of vertical ribs, horizontal ribs and diagonal ribs with varying angular orientations were used to reinforce the design, while consuming 1.99 lb of material. The final design satisfies all the functional and engineering requirements. At the same time, amount of material is reduced by 2.9% than the preliminary company design, as shown in Fig. 2(b). Although consuming less material is the result of interactive design instead of the direct consequence of feature-based approach, however, the feature-based cyclic design-analysis process helps to track and enable rib feature changes in a systematic manner which results in reduced data association time by the designer, and hence shortens product development time.

5. CONCLUSIONS AND FUTURE WORKS

This paper introduces a cyclic plastic part design and analysis engineering management methodology with the advanced feature-based approach. The benefit of this approach is that the data interdependencies can be managed in a more robust manner. It captures all the related product and process information in the feature data structure, such as specification features, conceptual features, CAE features, molding features and cost features. The relationships among inter-dependent features can be defined in the feature-based information model for multiple aspects, and thus information consistency across engineering models can be ensured. In the authors' experience, during the iterative design and FEA analysis cyclic process, the consistent design is ensured to fulfil pre-defined strength criteria and customer requirements. A case study for iterative design model evolvement is given based on structural performance analysis. Currently, a prototype software implementing the methodology is underway by using NX API functions; the details, such as data exchange automation, can be expected in the next paper. The experience we have had proves that the methodology based on feature concepts, ranging from modeling, implementation and tracking of the cyclic processes between CAD modeling and other engineering analysis aspects, ensures capturing design intentions early in the process, and guides the design modifications towards fulfilling preset criteria. The future work will include mapping CAD and CAE features and prototyping a functional module to verify the scalability and the effectiveness of the proposed methodology with a more cases. Then, associative modeling of specification, design, CAE and cost features is to be further investigated for automated change evaluation and propagation.

ACKNOWLEDGEMENTS

The authors would like to acknowledge NSERC's financial support via DISCOVERY and ENGAGE grants. They are also grateful for the technical input provided by Drader Manufacturing Industries Ltd.

REFERENCES

[1] Arabshahi, S.; Barton, D. C.; Shaw, N. K.: Steps towards CAD-FEA integration, Engineering with Computers, 9, 1993, 17–26. http://dx.doi.org/10.1007/BF01198250

[2] Bronsvoort, W. F.; Bidarra, R.; van der Meiden, H. A.; Tutenel, T.: The increasing role of semantics in object modeling, Computer-Aided Design and Applications, 7(3), 2010, 431–440. http://dx.doi.org/10.3722/cadaps.2010.431-440

[3] Deng, Y.-M.; Britton, G. A.; Lam, Y. C.: Towards automatic shape modification in injection-moulded-plastic-part design, International Journal of Advanced Manufacturing Technology, 28, 2006, 495–503. http://dx.doi.org/10.1007/s00170-004-2388-9

[4] Fenves, S. J.: A core product model for representing design information, National Institute of Standards and Technology, 2002.

[5] Gao, S.; Zhao, W.; Lin, H.; Yang, F.; Chen, X.: Feature suppression based CAD mesh model simplification, Computer-Aided Design, 42(12), 2010, 1178–1188. http://dx.doi.org/10.1016/j.cad.2010.05.010

[6] Gujarathi, G. P.; Ma, Y.-S.: Parametric CAD-CAE integration using a common data model, Journal of Manufacturing Systems, 30, 2011, 118–132. http://dx.doi.org/10.1016/j.jmsy.2011.01.002

[7] Hamri, O.; Leon, J.-C.; Giannini, F.; Falcidieno, B.: Software environment for CAD/CAE integration, Advances in Engineering Software, 41, 2010, 1211–1222. http://dx.doi.org/10.1016/j.advengsoft.2010.07.003

[8] Hoffmann, P.; Feng, S. C.; Ameta, G.; Ghodous, P.; Qiao, L.: Towards a multi-view semantic model for product feature description, Advanced Concurrent Engineering, 2008, 205–213.

[9] Jia, M.; Ding, G.; Qin, S.; Li, R.; He, Y.: Research of design and analysis integrated information modeling framework for multibody mechanical system: with its application in the LHD design, International Journal of Advanced Manufacturing Technology, 66, 2013, 2107–2122. http://dx.doi.org/10.1007/s00170-012-4485-5

[10] Lee, S. H.: A CAD–CAE integration approach using feature-based multi-resolution modeling techniques, Computer-Aided Design, 37, 2005, 941–955. http://dx.doi.org/10.1016/j.cad.2004.09.021

[11] Li, S.-H.; Chen, J.-L.; Yen, D. C.; Lin, Y.-H.: Investigation on auditing principles and rules for PDM/PLM system implementation, Computers in Industry, 64, 2013, 741–753. http://dx.doi.org/10.1016/j.compind.2013.04.007

[12] Ma, Y.-S.; Chen, G.; Thimm, G.: Change propagation algorithm in a unified feature modeling scheme, Computers in Industry, 59, 2008, 110–118. http://dx.doi.org/10.1016/j.compind.2007.06.006

[13] Ma, Y.-S.; Chen, G.; Thimm, G.: Paradigm shift: unified and associative feature-based concurrent and collaborative engineering, Journal of Intelligent Manufacturing, 19, 2008, 625–641. http://dx.doi.org/10.1007/s10845-008-0128-y

[14] Ma, Y.-S. (Ed.): Semantic Modeling and Interoperability in Product and Process Engineering, Springer, London, 2013. http://dx.doi.org/10.1007/978-1-4471-5073-2

[15] Malloy, R. A.: Plastic part design for injection molding - an introduction, 2nd Edition, Hanser Publications, Cincinnati, 2011.

[16] Rachuri, S.; Subrahmanian, E.; Bouras, A.; Fenves, S. J.; Foufou, S.; Sriram, R. D.: Information sharing and exchange in the context of product lifecycle management: role of standards, Computer-Aided Design, 40, 2008, 789–800. http://dx.doi.org/10.1016/j.cad.2007.06.012

[17] Shah, J. J.: Assessment of feature technology, Computer-Aided Design, 23(5), 1991, 331–343. http://dx.doi.org/10.1016/0010-4485(91)90027-T

[18] Shen, W.; Hao, Q.; Li, W.: Computer supported collaborative design - retrospective and perspective, Computers in Industry, 59, 2008, 855–862. http://dx.doi.org/10.1016/j.compind.2008.07.001

[19] Shephard, M. S.; Beall, M. W.; O'Bara, R. M.; Webster, B. E.: Toward simulation-based design, Finite Elements in Analysis and Design, 40, 2004, 1575–1598. http://dx.doi.org/10.1016/j.finel.2003.11.004

[20] Smit, M. S.; Bronsvoort, W. F.: Integration of design and analysis models, Computer-Aided Design and Applications, 6(6), 2009, 795–808. http://dx.doi.org/10.3722/cadaps.2009.795-808

[21] Sudarsan, R.; Fenves, S. J.; Sriram, R. D.; Wang, F.: A product information modeling framework for product lifecycle management, Computer-Aided Design, 37, 2005, 1399–1411. http://dx.doi.org/10.1016/j.cad.2005.02.010

[22] Vandenbrande, J. H.; Requicha, A. A. G.: Spatial reasoning for the automatic recognitions of machinable features in solid models, IEEE Transactions on Pattern Analysis and Machine Intelligence, 15(12), 1993, 1269–1285. http://dx.doi.org/10.1109/34.250845

[23] Xiao, A.; Bryden, K. M.; McCorkle, D. S.: VE-suite: a software framework for design-analysis integration during product realization, Proceedings of ASME IDETC/CIE conference, 2005, 859–867.

[24] Xu, X.; Wang, L.; Newman, S. T.: Computer-aided process planning - a critical review of recent developments and future trends, International Journal of Computer Integrated Manufacturing, 24(1), 2011, 1–31. http://dx.doi.org/10.1080/0951192X.2010.518632

[25] Xue, D.; Yang, H.: A concurrent engineering-oriented design database representation model, Computer-Aided Design, 36, 2004, 947–965. http://dx.doi.org/10.1016/j.cad.2003.09.013