APEM journal **Advances in Production Engineering & Management** 4 (2009) 4, 207-220
ISSN 1854-6250 Scientific paper

A THEORETICAL FRAMEWORK FOR CONCURRENT INTEGRATION OF CAD WITH DOWNSTREAM APPLICATIONS

Ullah, H.
NWFP University of Engineering and Technology Peshawar, Pakistan
e-mail: hamidullah@nwfpuet.edu.pk, Ph: (092) (091) 9216499

Abstract:
The paper presents a theoretical model for the integration of CAD with downstream activities of a product, in concurrent engineering environment, using STEP standard.

A feature-based approach is used in the model since features are considered as the main factor in integration of CAD with downstream applications. Feature conversion is used to transform features from one application model to another. STEP standard is used for data exchange and information sharing between the multiple applications of a product development. To achieve the design of a product to be easy for manufacturing and assembly, and at the same time be cost-effective, Design for Manufacturing (DFM) and Design for Assembly (DFA), the most common and popular DFX tools are mentioned.

Using the model, the designer may design products using concurrent engineering philosophy, so that possible design errors can be foreseen and thus corrected in the early design stage. As a result, the total cost and time for developing a product will be significantly reduced.

Future work will include the implementation of the framework to a real life problem. This paper presents a new theoretical model for the integration of CAD with downstream applications of a product, in concurrent engineering environment, using STEP as a standard.

Key Words: Integration, Feature-Based Modelling, Concurrent Engineering, Design for Assembly, Design for Manufacture, STEP

1. INTRODUCTION

1.1 Concurrent Engineering

In today's highly competitive global market, manufacturing companies are facing many critical issues such as how to develop a product in less time and at lower cost. Companies are finding that conventional manufacturing practices and tools can no longer keep pace with the fast changing customer’s demand in the global market. Increasingly, companies are trying to adopt strategic initiatives such a concurrent design and manufacturing in order to avoid the costly and time consuming activities associated with conventional design and manufacturing approaches [12].

Concurrent engineering, sometimes referred to as simultaneous engineering, is best described as: a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support. This approach is intended to cause the developers, from the outset, to consider all elements of the product life-cycle from conception through disposal, including quality, cost, schedule, and user requirements [30]. Concurrent engineering is defined as “designing for assembly, availability, cost, customer satisfaction, maintainability, manageability, manufacturability, operability, performance, quality, risk, safety, schedule, social acceptability, and all other attributes of the product” [9].

Concurrent engineering philosophy advocates, in fact, the product and process design activities to be carried out simultaneously with the aim of minimizing the product life-cycle cost and the time to market while providing high added value products for the customer satisfaction [3]. Concurrent engineering (CE) and associated techniques such as Design For Manufacture (DFM) and Design For Assembly (DFA) aim to reduce the developmental lead time of the component along with its cost by considering a proposed design solution in terms of ease of manufacture as early in the product development process as is practicable. Such techniques have resulted in substantial cost reduction as well as decrease in lead time [21].

If a product can be designed by concurrent engineering, possible design errors can be foreseen and thus corrected early. Consequently, the total cost and time for developing a product will be significantly reduced. In practice, however, it is an arduous task to consider all aspects of the product manufacturing cycle at the early design stage. This is primarily due to three major sources of difficulty: the complexity of the design process itself, the large volume and large variety of life cycle information, and the separation of life cycle functions. To overcome these difficulties, a number of methods have been developed in concurrent engineering, including Quality Function Deployment (QFD), the Taguchi Method, Total Quality Management (TQM), Design for Manufacturing (DFM), Design for Assembly. In order to achieve the design of a product to be easy to manufacturer and assemble, and be cost-effective, DFM and DFA are especially important among these approaches.

1.2 Importance of Features

A feature is a carrier of product information which may aid design or communication between design and manufacturing, or between other engineering tasks. Features can be thought of as building blocks for product definition or for geometric reasoning [25]. Analysis of the developments in mechanical engineering on feature-based modelling shows that features are collections of information which have a semantic meaning to a particular view on a product-part [27]. Features are considered as the main factor in integration of CAD with downstream applications because various design and manufacturing data can be associated with a feature [10].

Features have applications in many areas of mechanical engineering such as design, process planning, and assembly planning. The features used in the design domain are called design features. The features used in the process planning domain are called machining features. The features used in the assembly planning domain are known as assembly features and are associated with assembly-specific information [12].

The features and the information about features, including non-geometric information, may comprise a dictionary or library, from which designers can retrieve features to design a product. For various machined parts, the geometric features have specific relationships that correspond to the manufacturing and assembly operations [7]. A feature taxonomy can be developed for machined parts. In order for these design features to be readily used by CAD/CAPP/CAAP applications, the features in the taxonomy can be able to be transformed and mapped onto STEP features.

1.3 Important Types of Features

Form features

Form features are particular configurations on surfaces, edges, or corners of a part [28]. Form features identify the combination of topological and geometric entities such as it makes practical sense during the various stages of the product life-cycle; for instance, shoulder and boss are examples of form features which are significant during design and manufacturing [29]. Since, form features can represent at least some aspects of design intent and part functionality, many research efforts have been conducted in techniques for deriving form feature information from a geometric database where form features are recognized, extracted and classified using algorithms.

Design features

Design features such as protrusion, slot, hole, rib, and slot are defined as a combination of abstract form features and design intents. The design intents include material features, precision features, and functional features. Material features specify material composition and condition information such as properties/specifications or treatment applied to materials and surfaces. Precision features specify geometric dimensions and tolerances, and surface finish. Functional features specify performance parameters, operating variables, or design constraints [11].

Machining features

A machining feature is defined as a shape that represents volumes to be removed by machining to obtain the final part geometry from the initial stock [1]. Figure 1 shows the machining features classification defined in STEP AP224.

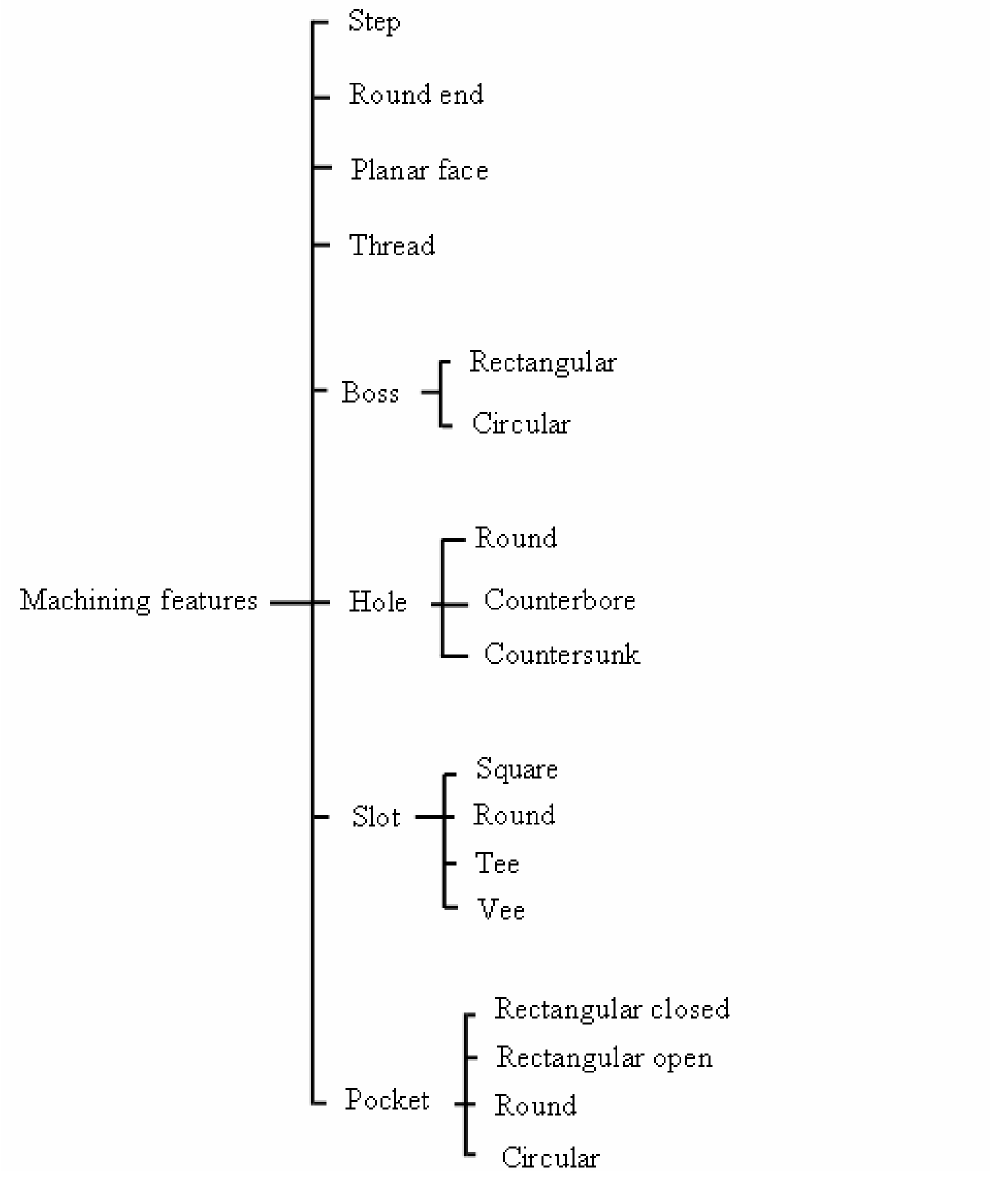


Figure 1: Machining features classification by STEP.

Assembly features

Assembly feature is defined as "a connection between two form features on mating parts, associated with assembly intents, where assembly intents include assembly relation, assembly operation, and assembly degrees of freedom" [14] as shown in Figure 2. Table 1 shows examples of assembly features.

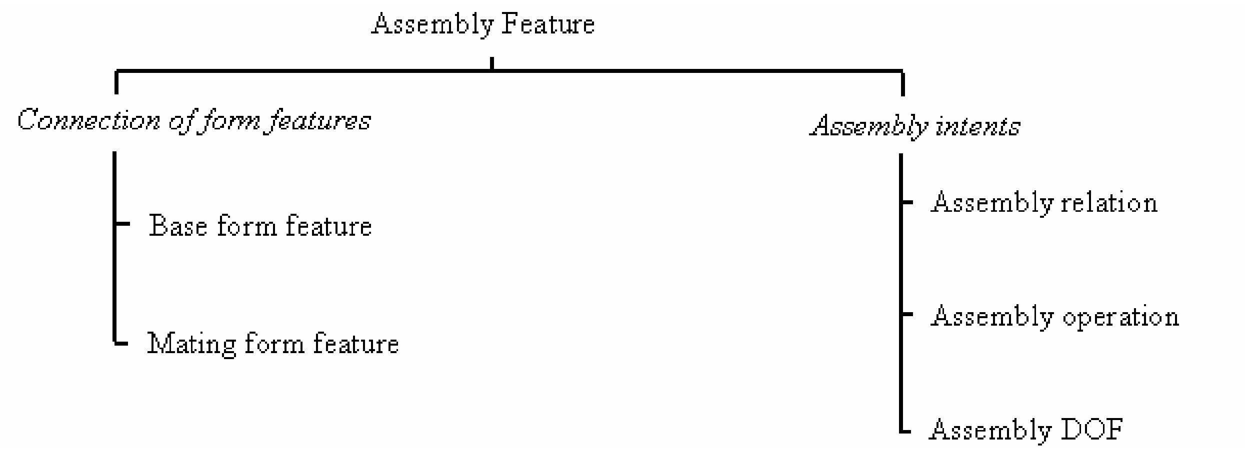
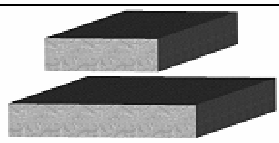
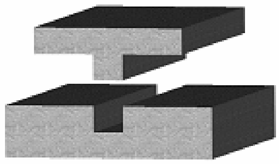
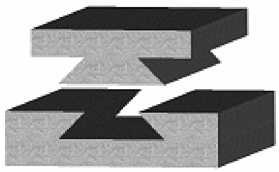
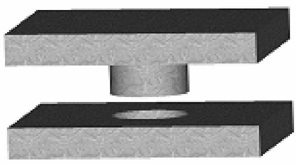
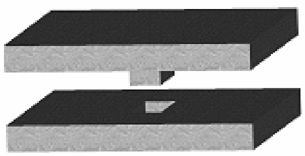


Figure 2: Assembly feature definition.

Table I: Examples of assembly features.

Assembly Feature	Geometric Shape
Plane-plane	
Rib-slot	
Dove-tail	
Circular Pin-hole	
Rectangular Pin-hole	

Assembly features can be used as a main factor in the integration of CAD with assembly planning because various design and assembly data can be associated with assembly feature. The integration of design and assembly planning is very important for achieving assembly oriented product development to reduce manufacturing cost and enhance the production efficiency and product quality. However, most of existing feature-based assembly research is displaying information to guide assembly modeling, planning, and integration, but there is lack of detailed research on assembly feature classification, which can offer an important foundation for modeling, planning, and integration of design with assembly planning. Not even the ISO produces a standard assembly feature classification, although they have for manufacturing features given by STEP AP 224. Therefore, assembly feature classification was made, as shown in Figure 3 [14].

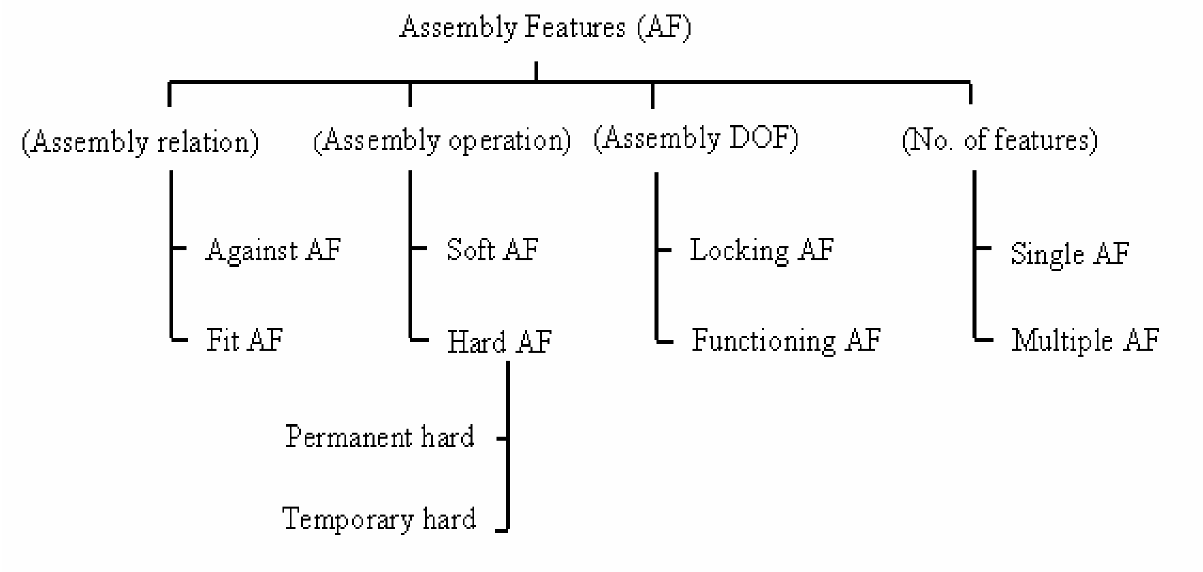


Figure 3: Assembly features classification.

Assembly features provide several useful information and advantages that facilitate the process of ASP. For example, assembly features give information on the precedence (or assembly order) of the components involved in the assembly of a product. They represent the prediction for the next component in the assembly to select in the sequence planning. They represent patterns of identical components. They also represent the mating of components through a number of features connecting together simultaneously. All these information result in a smaller number of assembly sequences that have to be checked in the assembly sequence optimization This can result in a significant reduction in the computation time for assembly sequence planning [13].

2. METHODOLOGY

This paper presents a theoretical model for integration of CAD with process planning and assembly planning. The main modules of the framework are: the CAD system, the assembly planning system, and the process planning system. Each module of the system is supported by additional sub-modules. The integration is achieved by the data flow that carries all the needed information through the various modules of the system. This integration can be used as an important step for achieving manufacturing and assembly oriented product development to reduce manufacturing costs and enhance the product quality and production efficiency.

Using Object-oriented approach part and/or assembly is modeled and represented by part features, assembly features, and their relationships. Based on the preliminary design information, when the attribute values of the features and their relationships are determined, then, these features, their relationships, and their associated attribute values become the input to the down stream applications: process planning and assembly planning systems. The features contain not only the part's geometric attributes, but also the information of the manufacturing and assembly processes, e.g., tolerance, surface finish, and manufacturing precedence and assembly precedence relationships.

The remainder of this paper is organized as follows. Framework for concurrent integration is provided in section 3. Section 4 describes compute-aided design (CAD) module of the framework. Feature-based design is mentioned in section 5. Section 6 describes the Standard for the Exchange of Product Data (STEP). Role of DFM and DFA is given in section 7. It is followed by the knowledge-based module in section 8. At the end, summary is given.

3. FRAMEWORK FOR CONCURRENT INTEGRATION

The available literature shows a lack of integration of design with the downstream activities of a product life-cycle. This dilutes the advantages of concurrent engineering. One of the growing solutions to this problem in industries is popular DFX tools like DFM and DFA. In addition, to resolve the information requirements for concurrent engineering, a computerized tool should be available. Therefore, feature-based design and feature conversion approaches which provide means to share common data between different domains of computerized tools are essential. These key findings reveal the need of concurrent integration of design with the downstream applications. The development of such a system is presented in this paper by a framework shown in the Figure 4. The main modules of the framework are: the CAD system, the assembly planning system, and the process planning system. These main modules are supported by sub-modules like, feature-based modeling, and pre-processor, process planning, Design for Manufacture (DFM), assembly planning, Design for Assembly (DFA), and STEP (Standard for the Exchange of Product model data). The framework illustrates the system structure, the functions of each module, and the information flow between the modules. Future work will include the implementation of the framework to a real life problem.

4. COMPUTER AIDED DESIGN (CAD)

CAD definition was best expressed by Mr. John Wright as he integrated the understanding of the design process with the analytical and graphic capabilities of the computer. CAD is a forum for the interaction of design information, people and technology. Since its inception, CAD has gradually been concerned with representing increasing amounts about the objects being manipulated. Geometric information has moved from 2D to 3D, and from planar to curved surfaces. Information about surface finish and color has been added. Geometric and Topological models specify the structural relationships between components. Descriptions of form features can be included. Application-specific information, such as material properties or manufacturing requirements is also useful. Thus CAD representations have moved closer to being a Knowledge Representation, to include all aspects of knowledge about the designed object. Suitable additions would be precise part-whole relations [31], the representation of function [26], and design rationale [19]. Researchers are concerned with what needs to be represented to support IntCAD systems, and with what progress has been made in IntCAD systems so far [6].

This module of the framework activates CAD software to create a CAD model for the product including drawing file and feature list. In order to develop the feature-based model of a part, the features and their relationships are recognized and extracted from a CAD data file. These features and relationships carry information of great importance to the design activities of a product and are therefore of great importance for the downstream applications of a product.

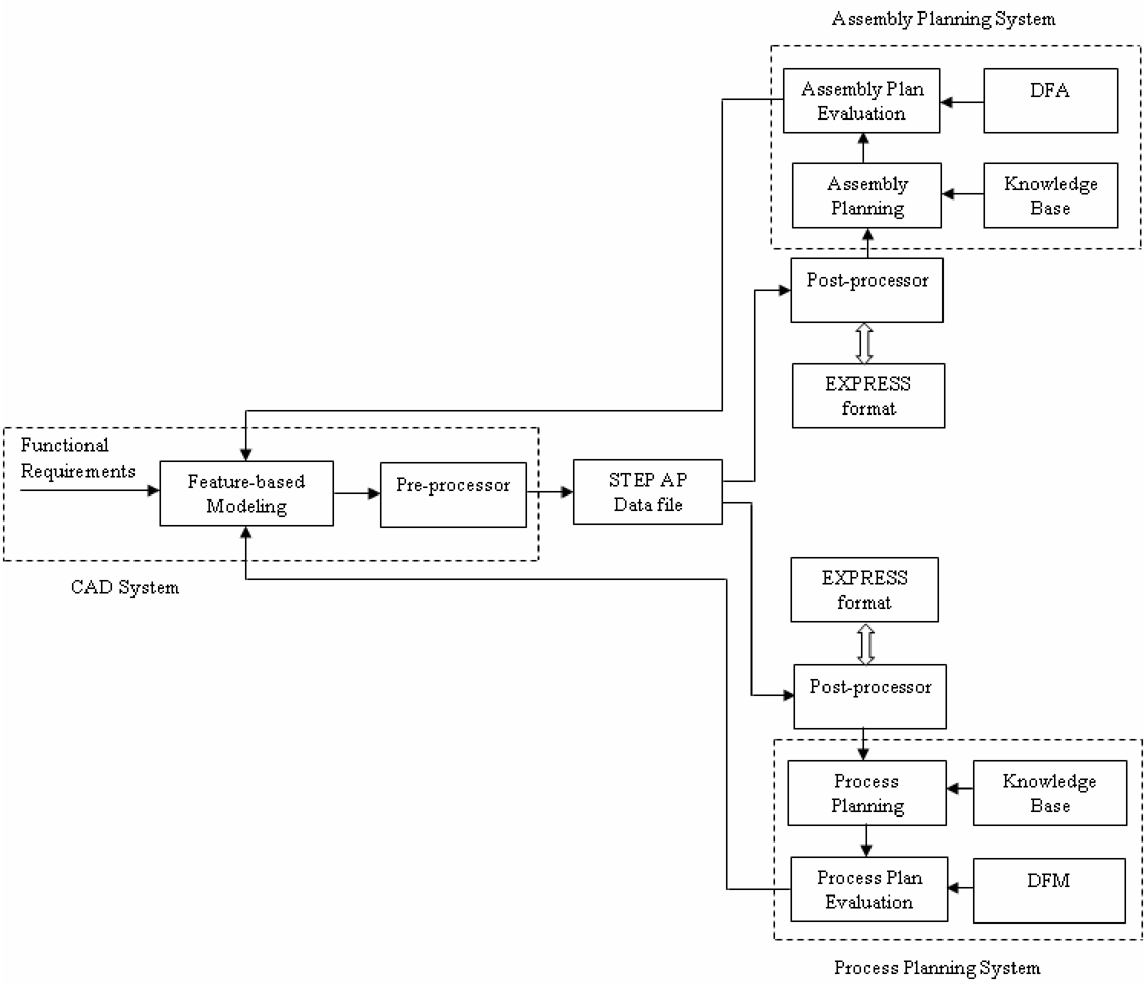


Figure 4: A framework for concurrent integration of CAD with process planning and assembly planning.

5. FEATURE BASED MODELING

It is more reasonable to construct a model in terms of meaningful entities, such as holes and bosses, and store that information, rather than recognize them after the fact. Much of research work has been conducted in the approach to define a part in terms of features instead of using low-level geometric entities. They are referred to as ‘‘design with features’’ or ‘‘feature-based design’’ [7]. The design by feature or the so-called feature-based design (FBD) approach builds a part from predefined features stored in a feature library. The geometry of these features is defined but their dimensions are left as variables to be instantiated when the feature is used in the modeling process. Feature-based design provides an explicit product data in a neutral format for direct use with downstream applications [1]. With feature-based design used as a key component of product representation in the whole product life-cycle, all product development activities such as CAD, process planning, and assembly planning, will be consistent and compatible with each other. For various machined parts, the geometric features have specific relationships that correspond to the manufacturing and assembly operations. One of the benefits of feature-based design is that features can be transformed, with varying degrees of difficulty, into other forms of representation useful for various concurrent engineering activities. Concurrent automation is possible with feature-based design and hence, holds more promise for concurrent engineering design. The implementation of the feature-based design method includes feature recognition, part representation, and design with features. Feature recognition is the understanding of a geometric model of an object to identify the relevant features and associated information.

Feature conversion, also called feature mapping, is defined as the process of deriving a feature model based on a particular point of view such as machining from a feature model based on a different point of view such as design [8]. In one-way feature conversion, typically, the feature models for the analysis and planning views are derived from the feature model of the design view. If the analysis or the planning results in the need to change the product model, then the changes have to be made in the feature model of the design view and the feature models for the other views can be automatically updated from that model. To allow the model of a product to be changed in the feature model of the view in which the need for it arises, multiple-way feature conversion has been developed [5]. Thus, feature conversion is considered as an important step towards full integration in concurrent engineering.

An advantage of feature conversion over feature recognition is the possibility of using non-geometric information stored in the existing feature model to derive the new feature model. Feature recognition has problems associated with the loss of data, incompleteness of design and manufacturing information and the complexity and computational load of feature recognition programs [15, 16, 32].

This module of the framework defines a part in terms of features and transforms features into other forms of representation useful for various concurrent engineering activities. Feature-based design method identifies the relevant features and associated information. In order to develop the feature-based model of a part or a product, the features and their relationships are recognized and extracted from an existing engineering drawing or from a CAD data file. It provides an explicit product data in a neutral format for direct use with downstream applications.

6. STANDARD FOR THE EXCHANGE OF PRODUCT DATA (STEP)

During the design stage of a part, a designer uses a CAD package and captures the characteristics of the part in a model that is wireframe, a boundary or solid geometry representation of the actual part. These geometric models are not suitable for retention of any kind of manufacturing features present in the part. Moreover, the implementation of the object modeling in the CAD database differs from one CAD vendor to another and thus any effort to extract the geometric information from the database directly will have to be specific to that software package. In other words, CAD files contain detailed geometric information of a part, which are not suitable for using in the downstream applications such as process planning and/or assembly planning. Different CAD or geometric modeling packages store the information related to the design in their own databases. Structures of these databases are different from each other. Therefore, a common or standard structure is required to be developed, that can be used by all CAD packages. In addition, the globalization of the market has increased competition, requiring a reduction in time-to-market for the cost-effective manufacturing of quality products Therefore, there is a great need to integrate and share information among different systems which are involved in the product development process. Here are many standards that support the data exchange, but all of them are mainly devoted to sharing geometric information. Only the ISO standard STEP (ISO-10303) deals with a more striving goal in transferring complete information related to the product development process [2].

STEP (Standard for Exchange of Product Model Data) is the outcome of a large international effort for the development of product and process model data standards for the purpose to enable data exchange between diverse computer systems and industrial applications for engineering, construction, and architecture. Thus, the overall objective of the standard is to become the world-wide standard for the representation and exchange of product model data [20].

The STEP standard provides detailed assembly design representations. These representations capture assembly structural and kinematics information during the design process. The model focuses on the hierarchy of the product, and on the position and orientation between parts. Based on the STEP standard, many new applications for product model data representation and exchange have been proposed, such as tolerance analysis and synthesis of assembly [18].

6.1 Feature Representation and Data Generation

In the proposed framework for integration, STEP is used because STEP application protocols support a wide variety of feature attributes Representation of feature attributes can become quite complex, making them difficult to define and understand. Therefore, STEP uses the EXPRESS language as a tool to represent product data in object-oriented and integrated environment. It is an object-oriented data descriptive language that classifies and constructs product data in terms of entities. It enables precision and consistency of product data representation and facilitates implementation. Each feature has an EXPRESS representation format (entity) which describes the attributes associated in the definition of that feature.

6.2 Pre-processing

The pre-processor is proposed in the proposed framework for integration to convert design data into a STEP XML data format. The pre-processor mechanism used in the translation process can be based on two layers. The first layer, known as logical layer, uses EXPRESS language to represent each feature in EXPRESS representation format which describes the attributes associated in the definition of that feature. The second layer, known as physical layer defines the communication file structure called STEP file. This file transfer mechanism represents the static aspect of STEP which allows exchange of product data. This file is obtained by translating the EXPRESS schemes defined in the logical layer to a STEP XML data format. An object-oriented approach can be implemented to facilitate the use of translation process from EXPRESS format to STEP XML format. All the EXPRESS schemes defining STEP features can be programmed in class files. Each feature has an algorithm that can use the EXPRESS class files to generate the required STEP feature data format.

The use of an object-oriented approach for the implementation of a product model offers a logical means for representing real-world objects such as machined parts. Therefore, in this approach each feature can be programmed in a class file with its public characteristics and operations. The inheritance feature of this approach can be used to define other common properties. It also allows interfacing with the operations required to be performed on the instanced feature. The four assembly features namely round pin-hole, threaded pin-hole, conical pin-hole, and rectangular pin-hole shown in Figure 5 are the instances of the pin-hole assembly feature. The pin-hole assembly feature is an instance of fit assembly feature which is a particular type of assembly features. The four instances of pin-hole assembly feature can be further instantiated. For example, the instance round pin-hole of the pin-hole assembly feature can be further instantiated into sub-instances of round pin-through hole and round pin-blind hole. The pin-hole assembly feature instance contains the properties and operations required to define the pin-hole assembly feature. Similarly, instances of the machine features are shown in Figure 1.

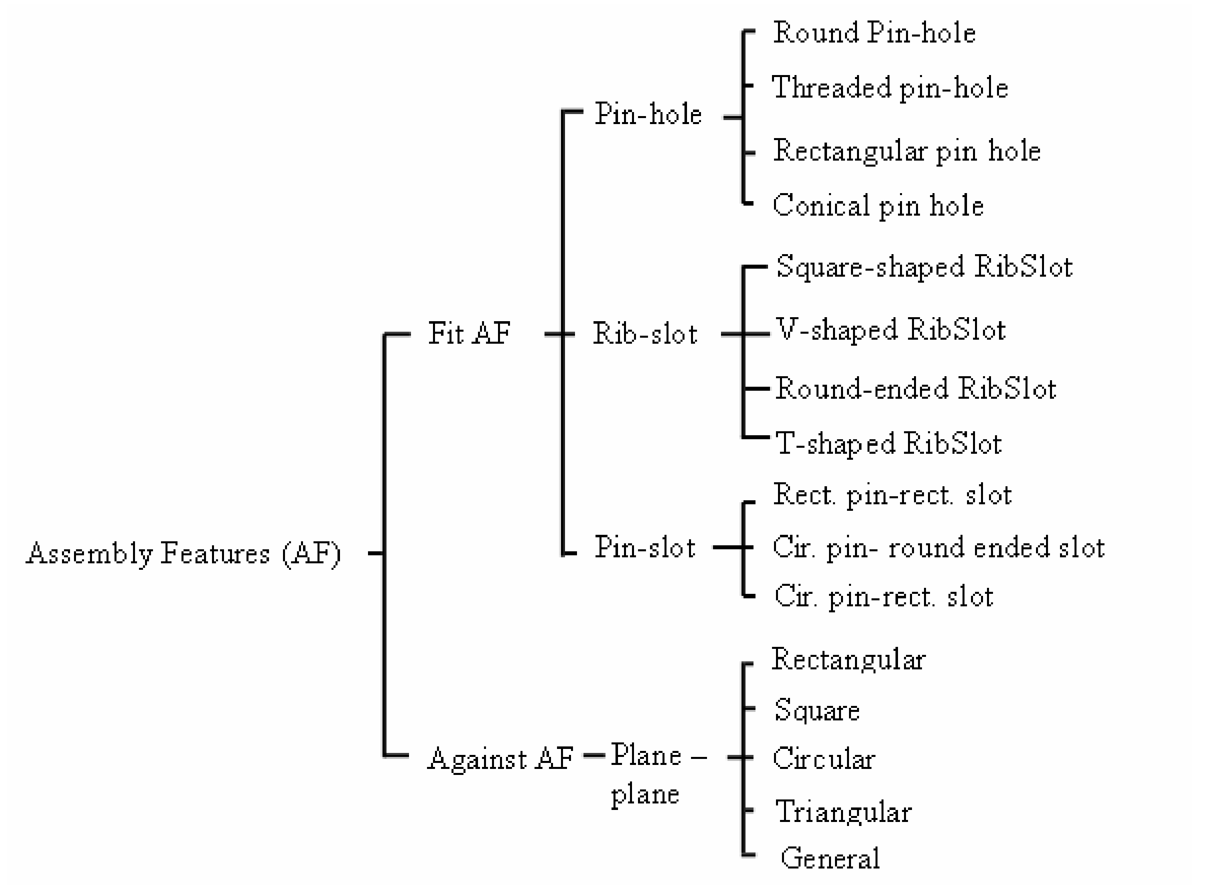


Figure 5: Assembly features instantiation.

7. DESIGN FOR MANUFACTUREAND DESIGN FOR ASSEMBLY

Researchers and manufacturing companies have developed design decision support tools with the aim to help designers better assess the downstream life cycle impacts of their design choices. These tools are referred to as Design for X (DFX) methodologies. The ‘X’ in DFX represents any one of a variety of design considerations occurring throughout the product life-cycle, such as assembly, manufacturing, quality, production, or environment. A DFX decision support tool can be a procedure or a set of guidelines on paper, or it can be a computer program that performs various types of analyses resulting in manufacturability cost, or performance estimates, which are used by the designer in making decisions. Design for Assembly (DFA) and Design for Manufacturing (DFM) are two of the most common and popular DFX tools [17].

Recent developments in DFM research and practice have led to incorporation of DFM techniques at a variety of design considerations occurring throughout the product development process, including conceptual design, embodiment design, detail design, and design verification. Moreover, DFM techniques now address a wide range of manufacturing and life cycle concerns including product life-cycle cost, manufacturing system performance, quality, and environmental issues [17].

In an overview, three main lines of DFM activities are given as follows [7].

- DFM Principles and Rules: To enable designers to consider manufacturability of the product early in the design process using DFM principles, rules and guidelines.
- Quantitative Evaluation Methods: To allow designers to rate the manufacturability of a design quantitatively.

- Computer Aided DFM: To use an appropriate set of principles and rules to help guide the design of the product and the to evaluate and redesign the product by using computerized tools.

Current DFA methodologies can be classified into the following basic types based on their analysis method [22].

- Specific assembly operation theories: To take a microscopic view of a particular design rule and its application to the assemblability of adjoining parts.
- Axiomatic approach: To follow two fundamental axioms (a) maintaining the independence of functional requirements and (b) minimizing the information content during the design process.
- Unstructured rules and guidelines: To provide general rules and guidelines for DFA.
- Procedural application of rules: To provide systematic procedures as detailed in written checklists or computer software.
- Artificial Intelligence-based approaches: To build a computerized system for DFA based on rule-based systems or using artificial intelligence constraint nets.

In addition to these guidelines, designers need to understand more about their own company's production system, i.e., its capabilities and limitations, in order to establish company-specific design rules to further guide and optimize their product design to the company's production system. For example, they need to understand the tolerance limitations of certain manufacturing processes.

DFA addresses assembly quality largely through product structure simplification and reduction in the total numbers of parts in a product [23]. Design for assembly (DFA) analyzes product designs in order to reduce assembly time and improve ease of assembly. This is achieved through a reduction in part count. The implementation of DFA techniques has played an important role in reducing costs of manufacturing over the last two decades [24].

One of the most widely recognized DFA methodologies has been formulated in which the DFA analysis considers redesigning an existing product through a two-step procedure applied to each part in the assembly [4]. The first step in this methodology evaluates each part for a candidate elimination or combination with other parts in the assembly. The second step estimates the time taken to grasp, manipulate and insert the part during assembly. Execution of the two steps allows a design efficiency rating to be calculated and used for comparison of different product designs.

Reducing assembly cost has become an urgent and potentially rewarding area to look into. DFA research is motivated by this desire for lowering assembly cost. The basic approach in DFA is to bring assembly considerations into the design phase since design is responsible for 75% of the final product costs. The traditional DFMA approach essentially focuses on obtaining a product with a high level of manufacturability. DFMA, in fact, attempts at minimizing production cost through simplification of product structure mainly resorting to a reduction of parts count, proper selection of the best combination of materials, geometry and cost-effective manufacturing methods for all parts, and simplification of manual assembly tasks. This implies that most DFMA techniques rate product designs on the basis solely of direct manufacturing and assembly costs. However, the DFM technique does not account for other design requirements which may be required simultaneously during the embodiment stage [21].

These sub-modules of the system are used as database in the framework for integration. It collects many design guidelines and industrial standards for mechanical products. This information will be used in evaluation of the process plans. DFM and DFA criteria is used to evaluate the design of mechanical products and obtain suggestions to improve the design in one integrated software environment. The key to concurrent engineering is the simultaneous consideration of design information throughout a product development life cycle, especially assembly and manufacturing. The use of DFM and DFA for decision making during the early stage is therefore important. Without an integrated environment in simultaneous engineering approach, the designers would not know if their designs may cause severe problems during manufacturing and assembly applications. DFM and DFA therefore is one of the growing solutions in industries for the concurrent integration of design, manufacturing and assembly activities in the design stage. To develop the framework for integration with DFM and DFA capabilities, use of a knowledge based approach becomes an important consideration.

8. KNOWLEDGE BASED MODULE

The execution of the knowledge-based module is an evaluation of a mechanical part and/or product. Rules in the knowledge-based system are divided into two levels. The rules in the first level are responsible for downloading part features, relationships, and industry standards. The rules in the second level check all the design guidelines for DFA, DFM and standardization based on part features and their relationships. To construct the knowledge base, collection of the necessary design guidelines and design standards is necessary.

The knowledge base module for manufacturing and assembly of parts consists of the design guidelines & strategies and design standards. Design guidelines and strategies are general design considerations which are usually accumulated from design experience and manufacturing practice. Design standards are standard sizes of part features that are commonly used in the industry and documented in mechanical design handbooks, e.g. drill size. Most of the guidelines are gained from the engineering design handbooks. The first part of the guidelines is the consideration of manufacturing processes that will render the part manufacturable. The second part of the guidelines is the consideration of assembly operations. The rest of the guidelines are can be used as the consideration of standardization and cost.

9. SUMMARY

Due to increasing competition in the manufacturing industry, the search for shorter product development and production cycles and lower cost has lead to the emergence of concurrent engineering. A number of methods have been developed in concurrent engineering In order to achieve the design of a product to be easy to manufacturer and assemble, and be cost-effective, DFM and DFA are especially important. To evaluate the feasibility and cost of manufacturing the product at the operation level DFM methods can be used. For the analysis of product designs in order to reduce assembly time and improve ease of assembly Design for assembly (DFA) methods can be helpful. Implementing DFM and DFA into one integrated system needs the use of knowledge-based system due to the growing needs for computerized application. However, without a feature-based design in common for the computerized DFM and DFA systems, not all design activities will be compatible and consistent with one another.

With feature-based design and modelling used as key components of product representation in the whole product life-cycle, all product development activities such as CAD, process planning, and assembly planning, will be consistent and compatible with each other. Features play a main role in the framework for integration. The design domain contains design features. Design features are converted into machining features and assembly features by feature conversion approach. Thus, integration is achieved by feature conversion approach from the design view to the downstream applications views of a product. By feature conversion, errors and modifications of a product development can be minimized in the early design stage of a product development. As a result, the total cost and time for developing a product will be significantly reduced. The integration can be used as an important step for achieving manufacturing and assembly oriented product development to reduce manufacturing costs and enhance the product quality and production efficiency. Therefore, there is a great need to integrate and share information among different systems which are involved in the product development process. STEP is used in the framework as a standard for the exchange of product model data.

10. ACKNOWLEDGEMENT

The author would like to express his sincere thanks to the anonymous referees for their insightful comments that helped in improving the quality of this paper.

REFERENCES

[1] Amaitik, S.M.; Kilic, S.E. (2002). A STEP-based product data model for CAPP, The Tenth International Conference on Machine Design and Production, 4 - 6 September 2002, Cappadocia, Turkey

[2] Ansaldi, S. (2003). On transferring and sharing design intent using STEP methodology, International Journal of Computer Applications in Technology, Vol. 18, No. 1-2, 93-104

[3] Antonio, C. C.; Pacifico M. P. (2008). Effects of product design on assembly lines performances: A concurrent engineering approach, Industrial Management & Data Systems, Vol. 108, No. 6, 726-749

[4] Boothroyd, G.; Dewhurst, P. (1989). Product Design for Assembly, McGraw-Hill Inc, New York

[5] Bronsvoort, W.F.; Noort, A. (2004). Multiple-view feature modeling for integral product development, Computer-Aided Design, Vol. 36, 929–946

[6] Brown, K. (1997). Grammatical Design, IEEE Expert, Vol. 2, No. 2, March/April

[7] Chen, K-H.; Chen, S. J.; Lin, L.; Wesley Changchien, S. (1998). An Integrated Graphical User Interface (GUI) for Concurrent Engineering Design of Mechanical Parts, Computer Integrated Manufacturing Systems, Vol. 2, 91-112

[8] Chitroda, M.; Sivaloganathan, S. (2007). Adequacy of machining features for describing machining jobs, International Journal of Industrial and Systems Engineering, Vol. 2, No. 2, 211 – 229

[9] Dean, E.B.; Unal, R. (1992). Elements of designing for cost, paper presented at The AIAA 1992, Aerospace Design Conference, Irvine, CA, 3-6 February, AIAA-92-1057

[10] Faraj, I. (2003). Manufacturing features: verification interaction accessibility and machinability, International Journal of Production Research, Vol 41, No. 10, 2249-2272

[11] Gao, J.; Zheng, D. T.; Gindy, N. (2004). Mathematical representation of feature conversion for CAD/CAM conversion system integration, Robotics and Computer Integrated Manufacturing, Vol. 20, 457-467

[12] HamidUllah (2007). Feature Based Sequence Planning And Assembly System Design Using Petri Net, PhD Dissertation, Asian Institute of Technology, Bangkok.

[13] HamidUllah and Bohez, E. (2008). A Petri Net Model for Sequence Optimization and Performance Analysis of Flexible Assembly Systems, Journal of Manufacturing Technology Management, Vol. 18, No. 8, 985-1003

[14] HamidUllah, Bohez, E.; Irfan, M.A. (2009). Assembly Feature Definition, Classification, and Usefulness in Sequence Planning, International Journal of Industrial System Engineering, Vol. 4, No. 2, 111-132

[15] Han, J. (1996). 3D geometric reasoning algorithms for feature recognition, PhD Dissertation, the University of Southern California, Los Angeles

[16] Han, J.; Requicha A. (1998). Feature recognition from CAD models, IEEE Computer Graphics and Applications, Vol. 18, No. 2, 80–94.

[17] Jeffrey W. H.; Cooper, J.; Gupta, S. K.; Hayes, C. C.; Ishii, K.; Kazmer, D.; Peter A. S.; Wood, W. H. (2004). New Directions In Design For Manufacturing, Proceedings of DETC'04 ASME 2004, Design Engineering Technical Conferences and Computers and Information in Engineering Conference September 28-October 2, 2004, Salt Lake City, Utah USA

[18] Kennicott, P.R. (1994). ISO TC 184/SC4: Product Data Representation and Exchange, Part: 44, Title: Industrial Automation Systems and Integration Product Data Representation and Exchange', Integrated Generic Resources: Product Structure Configuration (November 1994), ISO, Geneva.

[19] Lee, J. (1997). Design Rationale Systems: Understanding the Issues, IEEE Expert, Vol. 12, No. 3, May/June.

[20] Liu, M.; Lovett, P.; Godwin, N.; Fletcher, E. 'Improving the intelligibility of step models for the construction industry', Construction Informatics Digital Library http://itc.scix.net/paper w78-2000-584.content

[21] Mountney, S. L.; Gao, J. X.; Wiseall, S. (2007). A knowledge system to support manufacturing knowledge during preliminary design, International Journal of Production Research, Vol. 45, No. 7, 1521 -1537

[22] O'Grady, P.; Oh, J.S. (1991). A review of approaches to design for assembly, Concurrent Engineering, Vol. 1, No. 3, 5-l 1

[23] Redford, A.; Chal, J. (1994). Design for Assembly—Principles and Practice, McGraw-Hill Inc, England

[24] Robert B.S.; Daniel, A.M.; Varghese, J. (2004). A product architecture-based conceptual DFA technique, Design Studies, Vol. 25, No. 3, 301-325

[25] Shah, J.J.; Mantyla, M. (1995). Parametric and Feature-based CAD/CAM: Concepts, Techniques, and Applications, John Wiley and Sons, New York

[26] Umeda, Y.; Tomiyama, T. (1997). Functional Reasoning in Design, IEEE Expert, Vol. 12, No. 2, March/April

[27] Van Leeuwen, J.P.; Wagter, H.; Oxman, R.M. (1995). A Feature based approach to modeling Architectural Information. Modeling of buildings through their life-cycle. Proceedings workshop CIB W78 '95, Stanford University, CIB W78, 260-269

[28] Wang, N.; Ozsoy, T.M. (1990). Representation of assemblies for automatic tolerance chain generation, Engineering with Computers, Vol. 6, 121-126

[29] Wang, A.; Koc, B.; Nagi, R. (2005). Complex Assembly Variant Design in Agile Manufacturing. Part I: System Architecture and Assembly Modeling Methodology, Design and Manufacturing, IIE Transactions, Vol. 37, 1-15

[30] Winner, R.I.; Pennell, J.P.; Bertrand, H.E.; and Slusarezuk, M.M.G. (1988). The role of concurrent engineering in weapons system acquisition, IDA Report R-338, Institute for Defense Analyses, Alexandria, VA

[31] Winston, R.C.; Herrmann, D. (1987). A Taxonomy of Part-Whole Relations, Cognitive Science, Vol. 11, 417-444

[32] Yang, M.H. (1997). Recognizing machining features through partial constraint satisfaction, Systems, Man, and Cybernetics, Proceedings of the IEEE International Conference, Hyatto Rlandoo, Rlandof, Lorida, USA, 12-15 October, 1912–1917