Analysis and Evaluation for STEP-Based Electro-Mechanical Assemblies

Xuan F Zha[*], Sebti Foufou, Rachuri Sudarsan, Ram D Sriram

Manufacturing System Integration Division
National Institute of Standards and Technology
Gaithersburg, MD 20899

ABSTRACT

In this paper, we propose an integrated approach to assemblability analysis and evaluation for STEP-based (STandard for the Exchange of Product model data, officially ISO 10303) electro-mechanical products. First, two assembly representational models are brought up and elaborated: the EXPRESS/XML schema-based model and the NIST object-oriented UML-based Open Assembly Model (OAM). Then, these two models are integrated together, in which the OAM incorporates the EXPRESS/XML schema-based assembly model to completely capture the detailed geometric information. The proposed assembly evaluation approach uses the EXPRESS/XML schema-based model as the information source, and covers not only the geometric and physical characteristics of assembly parts but also the assembly operation data necessary to assemble the parts. The feature of this approach is the linkage of the STEP product definition to the fuzzy analytic hierarchy process (AHP) for assembly evaluation. The proposed approach has the flexibility to be used in various assembly methods and different environments. A case study shows the feasibility of the proposed approach.

Keywords: assemblability evaluation, design for assembly, assembly model, STEP, fuzzy analytic hierarchy process

1. INTRODUCTION

It has long been recognized that decisions made during the design stages have a great impact on the total cost of a product. Design for assembly (DFA) concerns assemblability analysis and evaluation and integrates the specific domain knowledge of product design, manufacturing and assembling, and decision-making automation in assembly process. The essence of DFA is to evaluate and rationalize the parts and assembly processes. The analysis of assembly properties of the product is needed during the initial design stage in order to identify potential assembly problems that may affect product performance in the later stages of its lifecycle. To design a low-cost product, designers need to know whether the designed product can be assembled and how difficult is the assemblability of its components. Assembly evaluation is a means to assess design quality in terms of assemblability or feasibility. The information feedback from such an analysis and evaluation process in the early design stage is a key to improve design quality for better assemblability.

During the assembly design process a set of solution alternatives is evaluated, and one solution is suggested based on the degree of satisfaction resulting from selection of alternative functional requirements. In view of assembly design as “generate and test,” the most important step in design decision making is the comprehensive evaluation and justification to find a final solution from a set of alternatives determined by multiple factors or suggested by many evaluators.

This research aims to propose an integrated approach to quantitatively analyzing and evaluating assemblability for assembly design based on STEP (ISO 10303). In the following sections, related work into assemblability or feasibility analysis is first reviewed in Section 2; Section 3 presents two assembly representation models: the EXPRESS/XML schema-based model and the object-oriented UML-based model, and discusses the EXPRESS/XML schema-based model for assembly evaluation; Section 4 presents a fuzzy AHP approach for evaluating the assemblability and the assembly sequence; Section 5 proposes a framework for integrated assembly evaluation; Section 6 provides a case study to verify and illustrate the proposed approach; and Section 7 gives a summary and some concluding remarks.

---

[*] Corresponding author, Email: zha@cme.nist.gov

2. REVIEW OF RELATED WORK

The related work on assemblability analysis and evaluation methods can be classified into three categories: design heuristics, design rating methods, and assembly geometric analysis. Based on these methods, there are many methodologies and systems developed for assemblability analysis and evaluation (Lim et al. 1995, Zha et al. 1998, Abdullah et al. 2003). In what follows, we give an overview of the related work on both assemblability analysis and evaluation methods and systems (Zha 2001). However, this is not a complete survey.

Most of the early work in the analysis of assemblability was rule based. The design attributes of the components, the assembly operations and relationships between components were used to estimate the ease or difficulty of the assembly. Plan-based evaluation systems were later developed to address the effects of sequencing assembling components on assemblability. The pioneering work of Boothroyd and Dewhurst (1989) in developing the design-for-assembly guidelines has resulted in several automated assembly evaluation and advisory systems (Jakiela 1989, Jakiela and Papalambros 1989, Zha et al. 1999, Zha 2001). Swift (1981) also presented a knowledge-based DFA technique with procedures similar to that of the Boothroyd and Dewhurst approach. Sturges and Kilani (1992) developed a semi-automated assembly evaluation methodology that attempts to overcome some limitations for the scheme proposed by Boothroyd and Dewhurst (1989). Although this system lacks geometric reasoning capabilities, it serves as an interactive environment to study the effect of various design configurations on assembly difficulty.

Li and Hwang (1992) developed another semi-automated system, which closely follows the Boothroyd-Dewhurst methodology. Their assembly difficulty analysis and cost-estimation modules were direct computer implementations of the DFA rules. Their method considers the multiple assembly sequences, calculates the time for all feasible sequences, performs limited feature recognition for assembly, and interactively obtains the non-geometric information that will affect the assembly. The final result is a table similar to a manual assembly worksheet. It is argued that assembly information developed quickly and in a proper format gives the designer enough input to perform further analysis for design modification.

The Hitachi Assemblability System (Miyakawa et al. 1981) has served as a basis for the development of an automated assemblability system. It is based on the principle of one motion per part, with symbols for each type of assembly operation, and penalties for each operation based on its difficulty. The method computes an assembly evaluation score and assembly-cost ratio. An assembly-cost ratio gives an indication of the current assembly cost to the previous cost. The methodology is common for manual, automatic and robotic systems.

Miles and Swift (1992) also developed an assembly evaluation method in which parts are grouped according to functional importance: “category A” parts are those required to fulfill the design specification, and “category B” parts are the accessories. The goal is to eliminate as many type-B parts as possible through redesign. Analyses of feeding and fitting were carried out on the parts, with both results combined into a total score. A proposed assembly sequence is used to perform fitting analysis. Warnecke and Bassler (1988) studied both functional and assembly characteristics. Parts with low functional value but high assembly difficulty receive low scores, while parts with high functionality and low assembly cost receive high scores. The scoring is used to guide the redesign process. An effective, efficient evaluation method should indicate the cause of design weakness by identifying the tolerance(s), form features(s), and geometry(ies) of assembly parts that cause the problem, rather than simply provide an evaluation score for the assembly parts or assembly operations.

The need for the integration of assemblability knowledge with current CAD systems has been motivated by the fact that DFA methods have the greatest impact on a product design when they are incorporated into the preliminary design stage (De Fazio et al. 1997). In these integrated CAD-DFA systems, a proposed design is evaluated and recommendations for improvements are presented based on the results of the evaluation. Liu and Fisher (1994) use a STEP-based mechanical system data model as the assembly evaluation information source. This organizes the assembly-related information in a feature-based fashion. The proposed general-purpose assembly evaluation method is built by adopting the basic concepts of multi-attribute utility theory. The feature of this method is the linkage of the STEP product definition to the assembly evaluation method. Zha (2002) proposed an integrated assembly evaluation method for STEP-based electro-mechanical systems. Jared et al. (1994) presented a DFA system that performs geometric reasoning based on mathematical models for assembly operations. This reduces the user input requirement. Their system calculates a manufacturability index for individual components and a fitting index between the components.

Artificial intelligence (AI) techniques, such as knowledge-based expert systems fuzzy set theory, and case-based reasoning, may be used for the integration of DFA and CAD (De Fazio et al. 1997, Abdullah et al. 2003).

Several methodologies and systems, such as IDAERS (integrated design for assembly evaluation and reasoning system), intelligent CAD-DFA, DFAES (design for assembly expert system) (Zha et al. 1999), the neuo-fuzzy system (Zha 2001), have been developed for integrated intelligent design for assembly (IIDFA). IDAERS can provide feedback on the estimated time required for assembling a product. Automatic identification of assembly attributes from a CAD description of a component has been investigated (Li and Hwang 1992). Jakiela and Papalambros (1989) developed an intelligent CAD system by encoding the Boothroyd DFA knowledge with feature-based representation. The system is able to provide users with suggestions in order to improve a design and also to help obtain better design ideas.

Assembly information models usually provide the input for assemblability evaluation methods. An assembly information model contains information regarding parts and their assembly relationships. There are some academic systems that offer some facilities to represent assembly information. One such system developed by Whitney and Mantripragada (1998) represents the high-level assembly information as the "key characteristics". The chains of dimensional relationships and constraints in the product are handled by the so-called Datum Flow Chain concept (Whitney 2004). One of the earlier works on assembly modeling was reported in (Lee and Gossard 1985). The system of van der Net (1998) focuses on designing assemblies taking into account requirements from the assembly process planning phase, in order to prevent design errors, reduce lead times, and be able to automate process planning. These requirements are captured in the assembly by specifying geometric, assembly and tolerance – specific relations on and between the assembled parts. Noort et al. (2002) did an excellent work on the integration of the views supporting parts design and assembly design of the whole product. Callahan and Heisserman (1997) proposed a strategy for evaluating, comparing, and merging design alternatives. Assembly features have also been subject to many studies (Shah 1991, Shah and Regers 1993, van Holland and Bronsvoort 2000, Coma et al. 2003, Chan and Tan 2003). Another very interesting work on assembly representation is the one related to the European Union funded project, known as MOKA (Stokes 2001).

From the review of the related work, we can conclude that although there are some *ad hoc* methodologies and systems developed for assemblability analysis and evaluation and a few efforts on the integration of assemblability knowledge with current CAD systems, the implementation of integration of assembly design, analysis and evaluation remains difficult due to interoperability limitations of current CAD and DFA systems. There is still a gap between the standardized representation of product data and information and the general-purpose assembly evaluation methods. To bridge the gap, this work aims to provide an integrated fuzzy analytic hierarchy process (AHP) approach to quantitatively analyzing and evaluating assemblability for assembly design based on the STEP. Through the next section, we present and discuss two models for assembly information representation: the NIST object-oriented UML-based Open Assembly Model (OAM) and an EXPRESS/XML schema-based model. The proposed assemblability evaluation fuzzy approach uses the second model (EXPRESS/XML based model) as the assembly information source.

3. ASSEMBLY REPRESENTATION MODELS

The standardization efforts support information exchange between different design, analysis, planning and evaluation systems. An integrated information model is the kernel for various kinds of applications in which features are used as the key integration elements. In this work, two assembly representation models are brought up and elaborated: the NIST object-oriented UML-based model (Sudarsan et al. 2003) and the EXPRESS/XML schema based model (Zha and Du 2002, Zha 2002). The former is UML object-oriented representation developed at NIST, which is called the Open Assembly Model (OAM). The latter is based on the STEP standard and combines EXPRESS/EXPRESS-G (ISO 10303-11, 14) and XML. As stated above, we integrate these two models together to completely capture the detailed geometric information. We are also exploring the integration of these two models using XML schema. The EXPRESS/XML schema based assembly model is used for the implementation purpose. Details are discussed below.

3.1 The NIST Core Product and Open Assembly Models

The NIST research effort towards the development of the basic foundations of the next generation of CAD systems suggested a core representation for design information called the NIST Core Product Model (CPM) (Fenves 2001) and a set of derived models defined as extensions of the CPM namely the OAM (Sudarsan et al. 2003).

The CPM has been developed to unify and integrate product or assembly information. It provides a base-level product model that is: not tied to any vendor software; open; non-proprietary; expandable; independent of any one product development process; capable of capturing the engineering context that is most commonly shared in product development activities. The core model focuses on artifact representation including function, form, behavior, material, physical and functional decompositions, and relationships among these concepts. It consists of two sets of classes, called object and relationship, equivalent to the UML class and association class, respectively.

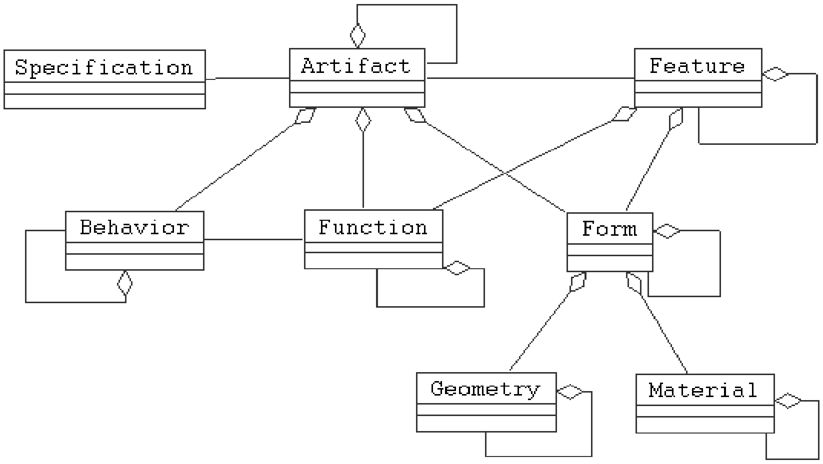


Figure 1: Entities in the Core Product Model

Figure 1 illustrates the principal entities of the CPM. An **Artifact** refers to a product or one of its components. It is the aggregation of **Function**, **Form** and **Behavior**. **Form** is the aggregation of **Geometry** and **Material**. In addition, an **Artifact** has attributes of **Specification** and **Feature**. **Specification** refers to the general information that contains all the design requirements pertaining to the artifact's function or form. **Feature** represents any information in the **Artifact** that is an aggregation of **Function** and **Form**; purely geometric constructs are not treated as features in the CPM. For more information on the CPM, including the relationships (associations) defined between the classes shown; please refer to (Fenves 2001).

OAM is extended from the CPM. It aims to provide a standard representation and exchange protocol for assembly and system-level tolerance information. OAM is still extensible; it currently provides tolerance representation and propagation, representation of kinematics, and engineering analysis at the system level (Sudarsan et al. 2003). The assembly information model emphasizes the nature and information requirements for part features and assembly relationships. The model includes both assembly as a concept and assembly as a data structure. For the latter it uses the model data structures of STEP.

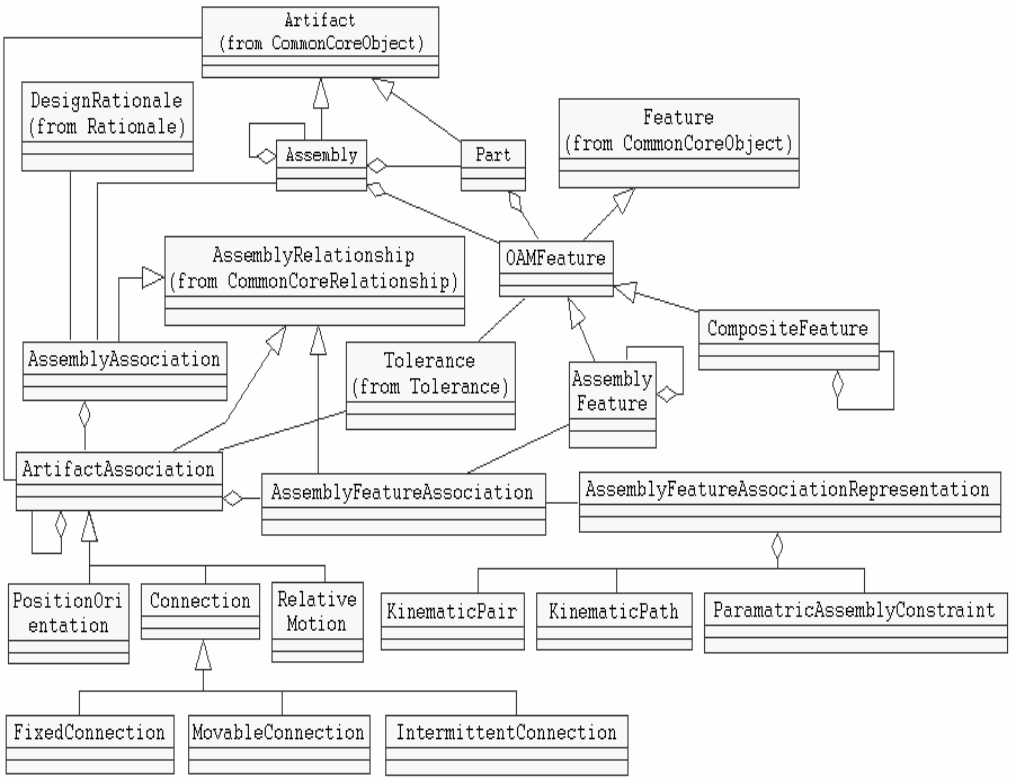


Figure 2: Main schema of Open Assembly Model

Figure 2 shows the main schema of the OAM. The schema incorporates information about assembly relationships and component composition; the former is represented by the class **AssemblyAssociation** and the latter is modeled using part-of relationships. The class **AssemblyAssociation** represents the component assembly relationship of an assembly. It is the aggregation of one or more **Artifact Associations**.

An **ArtifactAssociation** class represents the assembly relationship between one or more artifacts. In most cases, the relationship involves two or more artifacts. In some cases, however, it may involve only one artifact to represent a special situation. Such a case may occur when an artifact is to be fixed in space for anchoring the entire assembly with respect to the ground. It can also occur when kinematics information between an artifact at an input point and the ground is to be captured. Such cases can be regarded as relationships between the ground and an artifact. Hence, we allow the artifact association with one artifact associated in these special cases.

An **Assembly** is decomposed into subassemblies and parts. A **Part** is the lowest level component. Each assembly component (whether a sub-assembly or part) is made up of one or more features, represented in the model by **OAMFeature**. The **Assembly** and **Part** classes are subclasses of the CPM **Artifact** class and **OAMFeature** is a subclass of the CPM **Feature** class.

ArtifactAssociation is specialized into the following classes: **PositionOrientation**, **RelativeMotion** and **Connection**. **PositionOrientation** represents the relative position and orientation between two or more artifacts that are not physically connected and describes the constraints on the relative position and orientation between them. **RelativeMotion** represents the relative motions between two or more artifacts that are not physically connected and describes the constraints on the relative motions between them. **Connection** represents the connection between artifacts that are physically connected. **Connection** is further specialized as **FixedConnection**, **MovableConnection,** or **IntermittentConnection. FixedConnection** represents a connection in which the participating artifacts are physically connected and describes the type and/or properties of the fixed joints. **MovableConnection** represents the connection in which the participating artifacts are physically connected and movable with respect to one another and describes the type and/or properties of kinematic joints. **IntermittentConnection** represents the connection in which the participating artifacts are physically connected only intermittently.

OAMFeature has tolerance information, represented by the class **Tolerance**, and subclasses **AssemblyFeature** and **CompositeFeature**. **CompositeFeature** represents a composite feature that can be decomposed into multiple simple features. **AssemblyFeature**, a sub-class of **OAMFeature**, is defined to represent assembly features, a collection of geometric entities of artifacts may be partial shape elements of any artifact. For example, consider a shaft-bearing connection. A bearing's hole and a shaft's cylinder can be viewed as the assembly features that describe the physical connection between the bearing and the shaft. We can also think of geometric elements such as planes, screws and nuts, spheres, cones, and toruses as assembly features.

The class **AssemblyFeatureAssociation** represents the association between mating assembly features through which relevant artifacts are associated. The class **ArtifactAssociation** is the aggregation of **AssemblyFeatureAssociation**. Since associated artifacts can have multiple feature-level associations when assembled, one artifact association may have several assembly features associations at the same time. That is, an artifact association is the aggregation of assembly feature associations. Any assembly feature association relates in general to two or more assembly features. However, as in the special case where an artifact association involves only one artifact, it may involve only one assembly feature when the relevant artifact association has only one artifact.

The class **AssemblyFeatureAssociationRepresentation** represents the assembly relationship between two or more assembly features**.** This class is an aggregation of parametric assembly constraints, a kinematic pair, and/or a relative motion between assembly features.

ParametricAssemblyConstraint specifies explicit geometric constraints between artifacts of an assembled product, intended to control the position and orientation of artifacts in an assembly. Parametric assembly constraints are defined in (ISO 10303-108,109). This class is further specialized into specific types: **Parallel**, **ParallelWithDimension**, **SurfaceDistanceWithDimension, AngleWithDimension**, **Perpendicular**, **Incidence**, **Coaxial**, **Tangent**, and **FixedComponent.**

For a complete and more detailed description, including kinematic constraints modeling, tolerance specification modeling, etc. of the OAM, we refer interested readers to (Sudarsan et al. 2003).

3.2 EXPRESS/XML Schema-Based Assembly Model

The product model based on the hierarchical assembly model consists of **Assembly**, **Subassembly**, **Part** and **Connector** objects (Zha and Du 2002). It can be described by the EXPRESS schema and EXPRESS-G shown in Figure 3 below. As such, the OAM can be viewed as the shown EXPRESS-G (Figure 3) in a more detailed level.

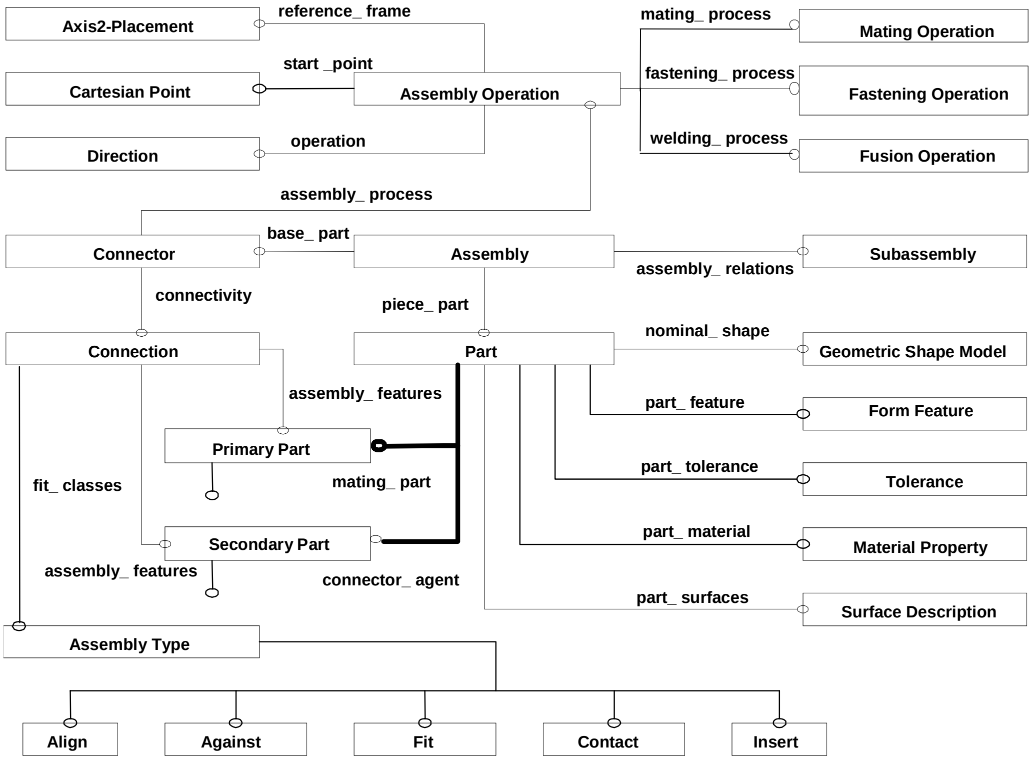


Figure 3: Assembly model in EXPRESS-G

The entity **Assembly** is the abstraction of common characteristics of products, which consists of several attributes including id, name, description, size, weight and subassemblies, parts, and assembly relations. A brief explanation of the product is stored in the attribute description. The attributed subassemblies, parts and assembly-relations have the type of **Subassembly**, **Part** and **Connector**. Since the history of product design should be recorded for the integrated system, the instances of the entity **Product-Version** (not shown in the figure) keeps the track of the product forms which consists of the attributed id, description, make-or-buy, and of-product of STEP (ISO 10303-41, 43, 44).

The entity **Subassembly** is defined as the subtype of **Assembly**, so that it can inherit the attributes of **Product** without being redefined. The inheritance mechanism provided by STEP simplifies the coding process and enhances the systems maintainability. The only difference between subassembly and product is that the subassembly is not a final product. The entity **Connector** should further express its upper structure and assembly relations with other parts or subassemblies.

The entity **Part** provides detailed information about a part. A part in a mechanical system is a solid entity that has specific geometry and material properties. Its attributes include id, name, code, nominal-shape, part-features, part-tolerances, material properties. The nominal-shape, part-features and part-tolerances correspond to parts of STEP: geometric model (ISO 10303-42), form features (ISO 10303-48) and tolerance (ISO 10303-47). A form feature adds detailed geometric characteristics to the geometric model to precisely define the shape of a part. Precision features such as tolerances and surface texture describe additional geometric characteristics of the final product design information for manufacturing and assembling such as assembly process and assembly method.

The entity **Connector** is defined based on the mating conditions and kinematics constraints between parts in the global product definition. From an assembling viewpoint, a connector is an ordered sequence of assembly operations and specifies assembly operations and mating conditions between parts. According to the way that parts are assembled, a **Connector** can be an operational connector, a fastener connector, or a fusion connector, in which a fastener connector contains additional information, i.e., its connector agent(s) with a designed part (such as a pin) or a standard mechanical part (such as a bolt and nut, screw, or rivet) used as a medium to assemble parts.

The information used by design and manufacturing can be classified into different features based on the information type. Form and precision features are defined in **Part** object above. **Assembly Features** are particular form features that affect assembly operations, which are defined by connectors (ISO 10303-109). The attributes of **Connector** include id, name, priority, connectivity and assembly process. **Connection** consists of **Primary Part, Assembly Type** and **Secondary Part**. **Primary Part** and **Secondary Part** are subtypes of **Part**; therefore, their necessary assembly features can be found in **Part** object. Meanwhile, assembly process is classified into mating operation, fastening operation and fusion operation. By the mating operation the mated parts have certain assembly relationship in position. The fastening operation fixes the connector agents and mated parts. The fusion operation joins the contact parts.

Therefore, the STEP integrated product information model comprises not only geometry but also form feature and product structure information (Zha and Du 2002, Zha 2002). Based on the conversion of EXPRESS schema to XML schema (ISO 10303-28), the XML representation for the assembly model can be generated. The partial listing of the generated XML schema from the EXPRESS schema for representing the generic assembly model is described below:

XML Schema

```
<?xml version="1.0" encoding="UTF-8"?>
<xsd:schema xmlns:xsd="http://www.w3.org/2001/XMLSchema">
  <!--XML Schema created by E2XS-->
  <xsd:element name="express_data">
    <xsd:complexType>
      <xsd:sequence minOccurs="1" maxOccurs="unbounded">
        <!--SCHEMA assembly-->
        <xsd:element name="Assembly">
          <xsd:complexType>
            <xsd:sequence minOccurs="0" maxOccurs="unbounded">
              <xsd:element ref="Assembly_Model" />
              <xsd:element ref="Part" />
              <xsd:element ref="Connector" />
              <xsd:element ref="Connection" />
              <xsd:element ref="Primary_Part" />
              <xsd:element ref="Secondary_Part" />
                ……
```

```
       <xsd:element ref="Operational_Connector" />
       <xsd:element ref="Fastener_Connector" />
       <xsd:element ref="Assembly_Operations" />
       <xsd:element ref="Assembly_Label" />
       ……
      </xsd:sequence>
     </xsd:complexType>
    </xsd:element>
   </xsd:sequence>
  </xsd:complexType>
 </xsd:element>
 <!--ENTITY Assembly_Model-->
 <xs:element name="Assembly_Model">
       <xs:complexType mixed="true">
          <xs:sequence minOccurs="0" maxOccurs="unbounded">
              <xs:element ref="subassemblies"/>
              <xs:element ref="piece_parts"/>
              <xs:element ref="assembly_relations"/>
          </xs:sequence>
       </xs:complexType>
   </xs:element>
<xs:element name="assembly_relations">
       <xs:complexType>
          <xs:sequence>
              <xs:element ref="Connector"/>
          </xs:sequence>
       </xs:complexType>
   </xs:element>
<xs:element name="Part">
   <xs:complexType mixed="true">
       <xs:sequence minOccurs="0" maxOccurs="unbounded">
          <xs:element ref="name"/>
          <xs:element ref="nomial_shape"/>
          <xs:element ref="part_features"/>
          <xs:element ref="part_material"/>
          <xs:element ref="part_surface"/>
          <xs:element ref="part_tolerances"/>
       </xs:sequence>
       <xs:attribute name="id" type="xs:string"/>
   </xs:complexType>
</xs:element>
……
</xsd:schema>
```

3.3 Comparison and Harmonization of the Two Assembly Models

From the implementation point of view the above two models are fundamentally different in the sense that the EXPRESS/XML schema assembly model is defined at a more detailed level using the EXPRESS and XML schema than the OAM defined using UML. From the assembly modeling point of view, the following points can be considered:

(1) The **Assembly Type** entity and its sub-entities (Align, Against, Fit, Contact, and Insert entities) of EXPRESS/XML model are covered in the OAM through classes derived from the **AssemblyFeatureAssociation** class;

(2) The **Assembly Operation** entity and its sub-entities (Axis2-Placement, Cartesian Point, Direction, Mating Operation, Fastening Operation, Fusion Operation) can be thought as an extension of OAM to represent assembly process;

(3) The remaining entities are already included in the OAM either under different names (e.g. the Geometric Shape Model and Material Property entities are covered in OAM through the Artifact class, which is an aggregation of CPM Function, Form, and Behavior classes) or relationships (e.g. the Subassembly entity is covered in OAM

through the containment relationship **subAssemblies/subAssemblyOf** illustrated in the figure by reflexive association on the Assembly class).

(4) Beside the entities of point 2 above, the OAM is more complete and includes a set of specialized classes for the representation of assembly features, kinematics, and tolerances, also when combined with CPM, the OAM can be used to capture information in various phases of the complete product realization process, from conception to assembly analysis and final process plan development (this is not shown in this paper, please refer to (Sudarsan et al. 2004) for more information.

To integrate and harmonize the above two models, we need to adopt the following steps:

1. The shadowed part of Figure 4 is added to OAM, which comes from the EXPRESS/XML schema based assembly model.
2. The type of assembly in the EXPRESS/XML schema based assembly model is covered in OAM through classes derived from **AssemblyFeatureAssociation**.
3. The operation of the EXPRESS/XML schema based assembly model can be thought as extensions of OAM to represent assembly process.

As stated before, the main aim of this work is at developing an integrated fuzzy AHP assembly evaluation approach. The EXPRESS/XML schema based assembly model is more suited for this application than the OAM, because it focuses on the detailed design, whereas the OAM focuses more on the conceptual design. The implementation of the EXPRESS/XML schema based assembly model and the definition of its equivalent XML Schema were already done (Zha and Du 2002, Zha 2002). The assembly evaluation approach proposed in this work is implemented and validated using this model as data source. Details are discussed in the next section.

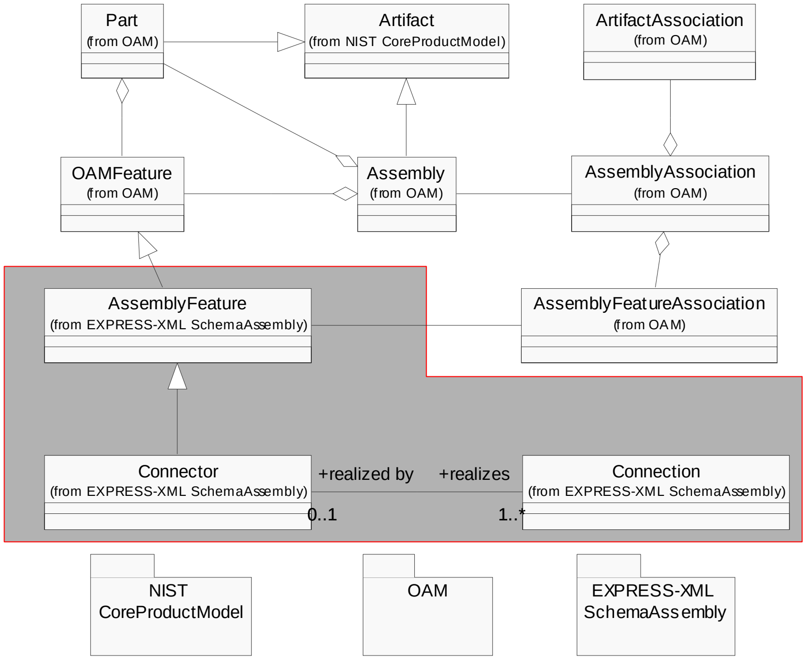


Figure 4: Integration of the above two assembly models

4. ASSEMBLY EVALUATION

Due to the uncertainty and fuzziness of design specifications and technical requirements, and the above parameters with different degrees of importance on the overall difficulty of assembly, it is difficult to assess the assemblability of the design using the traditional approaches reviewed in Section 2. In this section, a method for assembly evaluation is constructed using the analytic hierarchy process (AHP) approach proposed by Satty (1991) to multi-order fuzzy justification and evaluation problem, i.e., the fuzzy AHP approach.

4.1 Fuzzy Analytic Hierarchy Process

The AHP mechanism is known as an effective tool to support the multi-attribute decision-making. Its versatility in dealing with qualitative factors, multiple objectives, and decision makers has resulted in an impressive array of applications such as planning, conflict resolution, banking, architecture, etc. (Kim 2003). It is a compositional approach, in which a multi-attribute problem is first structured into a hierarchy of interrelated elements, and then a pairwise comparison of elements in terms of their dominance is elicited. The weights are given by the eigenvector associated with the highest eigenvalue of the reciprocal ratio matrix of pairwise comparisons. In AHP, it is possible to decide the weights by comparing the importance of two criteria subjectively. The pairwise comparison ratio which is comparison of the importance of criterion i and criterion j, that is w_i and w_j, is defined as:

$$a_{ij}= w_i /w_j \tag{1}$$

Considering a pairwise comparison matrix $A = [a_{ij}]$ and an importance index (weight) vector $W = [w_i]$, their relationship can be described as:

$$AW =nW \tag{2}$$

When A is given, the vector W and n are calculated as an eigenvector and an eigenvalue of A. The pairwise comparison matrix A should be examined whether the consistency is reliable. The consistency index (CI) is calculated as:

$$CI = \frac{\lambda_{\max} - n}{n-1} \tag{3}$$

where, $\lambda_{\max}$ is the maximum value of 0. If the value of CI is higher than 0.1, the matrix should be reset by comparing the importance again. Therefore, the focus of ranking/evaluation should be on the comparison matrix A. Currently, most of the research efforts in the AHP compose comparison matrix A according to user's individual and flexible preferences. In this work, we combine fuzzy membership functions with the AHP and pursue the preferences of users dynamically, and as a result, we could get the fuzzy comparison matrix A.

4.2 Assemblability Factors and Weights

To adopt the fuzzy AHP approach for assembly evaluation, the assemblability factors and their weights must be first identified. More details are discussed below.

4.2.1 Assemblability Factors

Considering the STEP-based assembly model discussed in Section 3.2, we classify the factors that affect the assemblability into two categories: geometry-based parameters and non-geometric parameters. Four types of characteristics of the parts and operations involved are of significance: the geometry characteristics (related to parts' geometry), the physical characteristics, the connection characteristics (related to the type of contact between the components), and the operation characteristics. These are described as an evaluation factor tree (Zha 2001): the geometric factor (α-symmetry, β-symmetry, number of ease of assembly form features), the physical factor (size, weight), the connection factor (fit type), and the operation factor (position, orientation, translation, rotation, force/torque). These different factors (parameters) have different degrees of importance on the overall difficulty.

4.2.2 Weight of Parameters

The widely used methods to find the relative importance of each parameter are: the pairwise comparison, the block distance, and the rank reciprocal rule (Ben-Arieh 1994). In this work, the above fuzzy AHP method is used. Assembly parameters are defined in terms of fuzzy linguistic descriptors, which can correspond to a range of actual parameter values (e.g., length), or to a qualitative description of a value of the parameter (e.g., interference). The fuzzy contribution of each parameter can be acquired based on expert advice, time study analysis, or even on experimentation with the various values of each parameter and analysis of the added difficulty. Fuzzy values are used to describe these parameters, and the values of the parameters are represented by linguistic variables with corresponding membership functions. For example, the interference expected in the assembly can be described as "low," "low-medium," "medium," "medium-high," and "high." Each such descriptor implies a certain degree of difficulty that is described as a three-tuple fuzzy number. For example, a fit of type "pressure fit" with "high" amount of force required implies a basic difficulty of

(26, 35, 55). A "push fit" with "low" force requires contributes difficulty of (16, 20, 26) to the assembly operations. The range of difficulty levels is from 0 to 100 with 100 representing an impossibly difficult operation.

As there are many factors involved, a multi-order (2-order) model is required to rank them for comprehensive fuzzy evaluation and justification for assembly. The first-order factors set can be described as: (u_{11}, u_{12}, u_{13}, u_{21}, u_{22}, u_{31}, u_{41}, u_{42}, u_{43}, u_{44}, u_{45}) =(α-symmetry, β-symmetry, number of ease of assembly form features, size, weight, fit type, position, orientation, translation, rotation, force/torque). The second-order factors set is described as: (u_1, u_2, u_3, u_4) = (geometric factor, physical factor, connection factor, operation factor).

The degree of importance for the first-order factors on assemblability can be described using a linguistic variables set - (very important, important, medium important, almost not important, no relation), while the degree of importance for the second-order factors on assemblability is described as a linguistic variables set - (almost not important, medium important, very important). Thus, expert advice can be collected to elaborate the contribution of each factor to assemblability. Using the consistence function, the relative values of linguistic variables can be determined and normalized. Hence, the weight of each first-order factor can be obtained as (0.0875, 0.0875, 0.175, 0.080, 0.040, 0.18, 0.065, 0.133, 0.042, 0.065, 0.042), and the weight of each second-order factor as (0.35, 0.12, 0.18, 0.35).

4.3 Fuzzy Evaluation of Assemblability

The assemblability can be evaluated through fuzzy value measurement using analytic hierarchical decision analysis. Two models for fuzzy evaluation of assemblability are discussed in this section.

4.3.1 Fuzzy Hierarchical Evaluation Model

To evaluate the assemblability of a design, each assembly factor makes a different contribution. This can be represented by the membership function defined in the universe of discourse of linguistic evaluation variable set E=(v_1, v_2, …, v_l), e.g., E=(Low, Medium, High) or E =(very good, better, good, worse, bad, very bad). Thus the voting matrix or evaluation matrix can be derived as a form. The second-order and first-order voting matrices, R and r, can be shown as follows, respectively.

$$R = \begin{array}{cc} & \begin{array}{cccc} v_1 & v_2 & \cdots & v_l \end{array} \\ \begin{array}{c} \mu_1 \\ \mu_2 \\ \vdots \\ \mu_n \end{array} & \begin{pmatrix} z_{11} & z_{12} & \cdots & z_{1l} \\ z_{21} & z_{22} & \cdots & z_{2l} \\ \vdots & \vdots & \cdots & \vdots \\ z_{n1} & z_{n2} & \cdots & z_{nl} \end{pmatrix} \end{array} \tag{4}$$

$$r = \begin{array}{cc} & \begin{array}{cccc} v_1 & v_2 & \cdots & v_l \end{array} \\ \begin{array}{c} \mu_{11} \\ \mu_{12} \\ \vdots \\ \mu_{1m_1} \\ \mu_{21} \\ \mu_{22} \\ \vdots \\ \mu_{2m_2} \\ \vdots \\ \mu_{n1} \\ \mu_{n2} \\ \vdots \\ \mu_{nm_n} \end{array} & \begin{pmatrix} r_{11} & r_{12} & \cdots & r_{1l} \\ r_{21} & r_{22} & \cdots & r_{2l} \\ \vdots & \vdots & \cdots & \vdots \\ \vdots & \vdots & \cdots & \vdots \\ \vdots & \vdots & \cdots & \vdots \\ \vdots & \vdots & \cdots & \vdots \\ \vdots & \vdots & \cdots & \vdots \\ \vdots & \vdots & \cdots & \vdots \\ \vdots & \vdots & \cdots & \vdots \\ \vdots & \vdots & \cdots & \vdots \\ \vdots & \vdots & \cdots & \vdots \\ \vdots & \vdots & \cdots & \vdots \\ r_{(m_1+m_2+...+m_n)1} & r_{(m_1+m_2+...+m_n)2} & \cdots & r_{(m_1+m_2+...+m_n)l} \end{pmatrix} \end{array} \tag{5}$$

After carrying out the hierarchical analysis and statistics, we can obtain the percentage r_{ij} ($i = 1,...,(m_1 + m_2 + ... + m_n)$, j=1,…, l) and z_{ij} (i=1,…,n; j=1,…,l) of the evaluated values of each factor and its item with respect to the evaluation linguistic variable matrix E.

Let the evaluation vector be Z, the weight vector be W, and the evaluation matrix be R. As there may be many hierarchical-level factors to be considered in a complex design problem, it is reasonable to adopt a multi-order model to comprehensively evaluate the performance of an object. This is dependent on the hierarchical classification of the evaluation factors as described above. From the evaluation factors set above, we can define two-order evaluation models as such that are composed of $U=(u_i, i=1,\ldots,n)$ and $u_i = (u_{ij}, j = 1,\ldots, m_i)$. For the first-order model, the value matrix and its voting matrix are $w_i = (w_{ij}, j = 1,\ldots, m_i)$ and r_{ij}, respectively. Based on the definition of evaluation matrix, we have

$$z_i = w_i \circ r_i \tag{6}$$

and

$$z_i = \vee_{j=1}^{m_i} (w_{ij} \wedge r_{ij})(i = 1,\ldots, n) \tag{7}$$

where, $\dot{\vee}$ and $\dot{\wedge}$ are union and intersection operators. For example, typical operators in the fuzzy set theory are maximum and minimum, "+" (addition) and "-" (minus). For the second-order model, considering the first-order evaluation results, its voting and value matrices can be represented as $R = (z_i, i = 1,\ldots, n)$ and $W = (w_i, i = 1,\ldots, n)$ respectively. Thus, the final evaluation results are determined as follows

$$Z = W \circ R \tag{8}$$

4.3.2 Additive Aggregation Model

For a specific design or in a specific assembly environment, each assemblability factor has a reasonable range. Specifying a reasonable range for each factor constrains the evaluation method to provide a better response. For example, a 20 kg part may be considered heavy for manual assembly but light for robot assembly. In the fuzzy theory, a variable v can belong to more than one set, according to a given membership function, $\mu_X(v)$. The possible values of a linguistic variable are not numbers but so called linguistic terms, such as *S* (small), *M* (medium) and *L* (large). Standard membership function types as Z, λ, π and *S* type can be mathematically represented as piecewise linear functions. For example, the variable v=2.5 belongs to *S* with a membership grade $\mu_S(v)$=0.75 and to M with $\mu_M(v)$=0.25. As such, the acceptable range of each assemblability factor can be categorized by the grade. The grade of each assembly factor is subject to change for refining the resolution of an evaluation.

Based on the weight of parameters, the allocated score of each parameter can be obtained, and they can be easily used to evaluate the assemblability. This can be accomplished by evaluating the assemblability of a joint/connector. The major issue is how the ratings to different parameters are given. In practice, reference values from DFA should be used as a benchmark or they are user-defined with training/learning. If they are user-defined, it will vary a lot from what assembly workstations are deployed by a given company. Also, manual or robotic assembly makes a big difference. Therefore, the ratings should be assigned to remove ambiguity of ratings from one person to the other.

With respect to the STEP-based model, the following two types of joints/connectors are considered: the fastener joint (with joint agent, e.g., screw, pin, bolt and nut) and the operational joint (without joint agent) (Zha 2001):

(1) For an operational joint, the secondary part is mated into the primary part, and the assembly difficulty score as an Assembly Evaluation Index (AEI) is calculated using the following equation:

$$AEI\ (J) = \frac{1}{100} \sum_{i=1}^{n} ds_i(x_i) \tag{9}$$

where, $ds_i(x_i)$ is the relative difficulty score of the joint for the *i* assembly factor. AEI (J) is the assembly difficulty score of Joint J, which is regarded as an assemblability evaluation index of Joint J.

(2) For a fastener joint, the primary part and secondary parts are mated together first, and then the joint agents are used to join the mated parts. Assuming all the assembly characteristics of the mated parts and the agents are equally important, the assembly score for a fastener joint is calculated as follows:

$$AEI\ (J) = \frac{1}{100p} \sum_{j=1}^{p} \left(\sum_{i=1}^{n} [ds_i(x_i)]_j \right) \tag{10}$$

where, p is the total number of secondary parts and agents involved in the fastener joint. Here, one can note that the treatment of fastener joints does not fully represent the importance of fastening methods and their selection in DFA.

4.4 Assembly Operation Sequence Evaluation

In the previous section, we discussed the fuzzy assemblability evaluation based on the degree of difficulty of assembly operations. As a matter of fact, once the mating operation is evaluated, the entire sequence of operations can be evaluated. The evaluation of the entire sequence of operations needs to support comparison and selection of a preferred one; therefore, the aggregate measure of difficulty for the entire sequence of operations is represented as a fuzzy number between 0 and 1. Suppose that the following notation is used: S_i= sequence i, i=1, ..., n; n_i = number of operations in sequence S_i, S_{ij} = operation j in sequence i,j=1,...,n_i; ds_{ij} = assembly difficulty score that represents the degree of difficulty of operation j in sequence i. For the entire sequence, the assembly difficulty scores for the sequence i can be calculated using the following equation:

$$SEI\ (S_i)= \frac{1}{100n_i}\{\sum_{i=1}^{n_{i1}} ds_i(x_i) + \frac{1}{p}\sum_{k=1}^{p}(\sum_{j=1}^{n_i - n_{i1}}[ds_j(x_j)]_k)\} \quad (11)$$

where, SEI (S_i) is the sequence evaluation index of sequence i; n_i=n_{i1}+n_{i2}, n_{i1} is the number of operational joints in sequence i, and n_{i2} is the number of fastener joints in sequence i; $ds_i(x_i)$ is the relative difficulty score of the joint for the i*th* assembly factor; p is the total number of secondary parts and agents involved in the fastener joint.

Based on Equation (11), the preferred sequence is chosen as the one with the lowest sequence evaluation index. It can be seen that the SEI value is a function of the number of operational joints, number of fastener joints, relative difficulty score of the joint, and the total number of secondary parts, and agents involved in the fastener joint. We note that the difficult score of each operation joint is evaluated using the comprehensive evaluation. For the entire sequence, it contains a lot of operations. If the application conditions are the same (not changed), taking the maximum rather than the average of difficulty score (*ds*), then the final sequence evaluation results should be the same as the proposed SEI in this work, but, of course, the value of *SEI* is different. To validate the evaluation methods and corresponding equations, an elaborate case study was undertaken. More details are discussed in Section 6.

5. AN INTEGRATED FRAMEWORK FOR ASSEMBLY ANALYSIS AND EVALUATION

The integrated assembly analysis and evaluation framework is shown in Figure 5, including modules like feature-based CAD, data and information modeling, STEP modeling, product modeling, assembly planning, and assembly evaluation. These modular systems correspond to the agent-based models defined in (Zha and Du 2002). The purpose of the product-modeling module is to provide mechanisms for representing, managing and exchanging product data using STEP. It is the central piece of the framework. The assembly-oriented product model is defined as numerous STEP entities from integrated resources (IR) written in EXPRESS and XML to meet the need of assembly design and planning. Once a product or parts of the product are designed, the product data, for example, hierarchical structure of assembly and assembly relations, etc., are generated by a feature-based CAD system. They are stored in the product model as instances of STEP entities. The feature-based CAD system can also accept the imported CAD files of individual components and assemblies and organize them into an assembly representation. In this context, by using feature recognition techniques (Sung et al. 2001), the assembly editor can differentiate connectors between parts and assembly features on individual parts. The assembly planning system obtains the necessary information from the product model through a preprocessor and generates the feasible assembly sequences (Zha and Du 2002, Zha 2004). The assembly planning system is implemented by incorporating several sub-modules, such as the geometric checking and reasoning module for interference and collision detection, precedence generation, user input constraints, a sequence generator, a Petri net tool for representing, analyzing and searching, simulating and visualizing as well as optimizing assembly sequences (Zha et al. 1998). The interference detection for disassembly operation is required for assembly sequence generation. The geometry checking employs a collision detection algorithm for every component in every candidate assembly direction. The objective is to determine the set of components that would obstruct the assembly operations if they were already in their final position, similarly, consider the disassembling of the final product. The precedence generation sub-module determines the precedence relationships among parts with a precedence graph. There are many constraints considered when planning assembly sequence. Allowing the user to input constraints or criteria on which assembly sequences are chosen helps to prune the number of feasible sequences. The sequence generator via a disassembly approach performs generation and construction of assembly plans. The assembly evaluation system is used to evaluate the design and planning results including the assemblability and assembly sequence. They are evaluated in terms of minimization of total assembly time or assemblability evaluation index (AEI) and assembly sequence evaluation index (SEI). The results of evaluation feed back to the redesign stage through the product model.

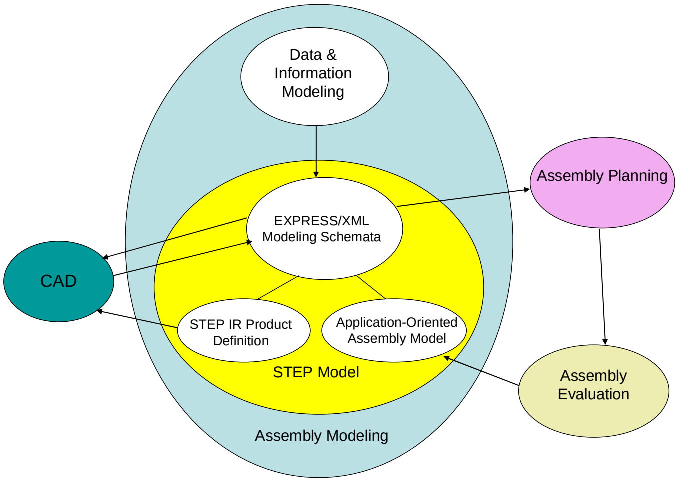


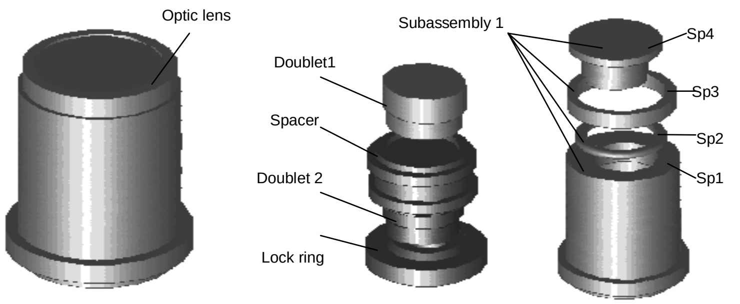
Figure 5: An overview of the framework for integrated assembly evaluation

Typically, these system components can be used in the following scenario. A designer creates an assembly model using the product-modeling module based on STEP. The designer then uses the planning module to generate and select the assembly sequence. During the course, the designer uses the assembly evaluation system to evaluate the design and planning results including the assemblability and assembly sequence. Thereafter, the designer can select the simulation module to compose a customized simulation. Based on the simulation feedback the designer may need to refine the assembly design. After several design iterations, the designer is satisfied with the design and hands it over to the process engineer.

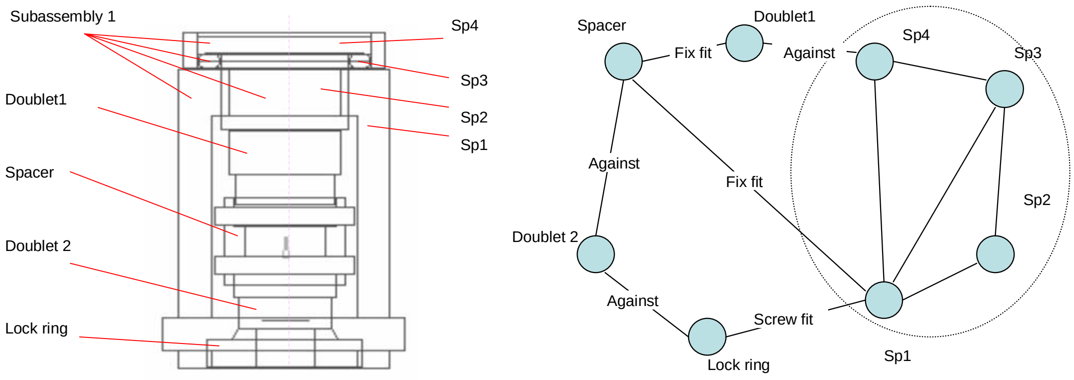
6. CASE STUDY

To verify and illustrate the proposed approach, an optic lens assembly with eight parts, as shown in Figure 6, is simulated. The assembly consists of eight parts labeled: 1-doublet 1, 2-spacer, 3-doublet 2, 4-lock ring, and 5-subassembly 1 (pre-assembled, composed of sp_1, sp_2, sp_3 and sp_4). Parts (Doublet 1, spacer, doublet 2, and lock ring) are connected with contact fits. Part (Lock ring) also connects sp_1 with a screw fit. The assembly is to be accomplished by a robot system. The assembled optic lens is a subassembly to be mated into a large assembly.

As discussed above, a unified description for the feature-based models of both an assembly and single piece components can be obtained through the data abstraction of components and connectors on various levels. Therefore, the feature models for the optic lens assembly consist of the components and a set of connectors: against, chamfer, face, cylinder, screw fit, and several cases of fix_fit, all of which are features as usual. In terms of the hierarchical model, part descriptions are form feature oriented, and product assembly structure descriptions are hierarchical multi-level graphs with feature-links.



(a) 3D Optic Lens



(b) 2D Cross-section drawing

(c) Assembly Liaison graph

Figure 6: Optic lens assembly

All these data and information comprise the main parts of the STEP model of the optic lens assembly. For instance, the entity definition (Table 2) and its XML representation for the part of lock ring can be described as follows:

Table 2: The entity definition for lock ring

part 4(O_4) {

Name	Lock_ring
ID	1001
nominal_shape	step_cylinder
part_features	[chamfer, fixfit, cylinder, screw_fit]
part_tolerances	[0.01]
part_material	[aluminum]
part_surface	[cylinder]

}

XML:

```
…
<part id="part 4">
    <name> Lock ring</name>
    <nomial_shape>
      <geometric_shape_model>step cylinders </geometric_shape_model>
    </nomial_shape>
    <part_features>
        <form_feature id="00013">
             <name>CLD 1</name>
             <type> cylinder</type>
             <diameter>0.024</diameter>
             <height>0.011</height>
        </form_feature>
```

```
            <form_feature> chamfer </form_feature>
            <form_feature> screw_fit</form_feature>
      </part_features>
      <part_tolerances>
            <tolerance>0.01</tolerance>
      </part_tolerances>
      <part_material>
            <material>aluminum</material>
      </part_material>
      <part_surface>
            <surface>cylindrical Surface</surface>
      </part_surface>
</part>
…
```

For illustration, the partial STEP file script for the optic lens assembly is given below:

```
ISO-10303-21;
HEADER;
/*----------------------------------------
 * Exchange File generated by ST-DEVELOPER v10
 * Conforms to ISO 10303-21
 *----------------------------------------/
FILE_DESCRIPTION (("), '1');
FILE_NAME ('Optic lens', '2003-10-03T14:08:21-04:00', ("), ("), 'ST-DEVELOPER v10', ", ");
FILE_SCHEMA (('CONFIG_CONTROL_DESIGN'));
ENDSEC;
DATA;
#10 = PLANE (", #40);
#20 = CARTESIAN_POINT (", (0., 2., 0.));
#30 = DIRECTION (", (0., 1., 0.));
#40 = AXIS2_PLACEMENT_3D (", #20, #30, $);
#50 = CYLINDRICAL_SURFACE (", #90, 0.0241);
#60 = CARTESIAN_POINT (", (0., -0.041, 0.));
……
ENDSEC;
END-ISO-10303-21;
```

After all connectors/joints are evaluated, the total assembly difficulty scores can be obtained by summing all of the evaluated scores of these joints. As different assembly sequences require different assembly operations, the total assembly difficulty scores are therefore different. For the sequence: doublet 2 → spacer → doublet 1 → lock ring → subassembly 1 (i.e., 3 → 2 → 1 → 4 → 5), the total assembly difficulty score is 11.93 and the assemblability evaluation index (AEI) is 0.1193 (0.12). The larger the value of AEI is, the more difficult the assembly. Thus, the AEI of 0.1193 makes very significant difference with the AEI of 0.1293 for an assembly. Table 3 shows an assembly difficulty evaluation for a mating operation in the assembly process. With the fuzzy hierarchical evaluation method, the evaluation result is (0.42, 0.71, 0.91), which means that the probability of good assemblability is high (>=70%). Here, the evaluation variable set is E= (Low, Medium, High). Thus, the assemblability can be considered as good.

Table 3: One mating operation assembly difficulty score evaluation

Mating Operation	Assembly Factors	u_{11}	u_{12}	u_{13}	u_{21}	u_{22}	u_{31}	u_{41}	u_{42}	u_{43}	u_{44}	u_{45}
	Data	360	0	2	5	2	LN	Clear	Vertical	4	0	0
	Score	4.66	0.59	1.75	0.64	0.40	4.5	0.0	1.67	0.60	0.00	0.00
	Total assembly difficulty score=11.93, assembly evaluation index=0.12											

All the feasible sequences for the optic lens assembly can be generated using the integrated knowledge-based approach proposed in (Zha et al 1998). There are 12 feasible assembly sequences remained after considering hard and soft constraints for linear assembly. Here, hard constraints are the geometric and physical constraints related to the generation of the assembly sequence, and soft constraints are imposed by assembly planners while evaluating and selecting an assembly sequence. Through the assembly sequence evaluation discussed above, the fuzzy evaluation of difficulty score and assembly sequence evaluation index (SEI) can be obtained. The assembly difficulty scores of four different assembly sequences (1 → 2→ 3→ 4→ 5, 3→ 2→ 1→ 4→ 5, 4 →3 →2 →1 →5, 5→ 3→ 2→ 1→ 4) are (0.52, 0.12, 0.28, 0.39) respectively. Therefore, among these four assembly sequences, the optimal one is 3→ 2→ 1→ 4→ 5.

7. CONCLUSIONS AND FUTURE WORK

There is still a gap between the standardized representation of product data and information and the general-purpose assembly evaluation method. To bridge the gap, this paper presented an integrated fuzzy AHP approach to evaluating assemblability and assembly sequence for STEP-based electro-mechanical products. The contribution of this work can be summarized as: 1) linking and harmonizing two STEP-based assembly models, 2) analyzing and extracting information from the assembly information models for assemblability evaluation, and 3) providing an integrated fuzzy analytic hierarchy process (AHP) approach to quantitatively evaluating assemblability for concurrent assembly design. The evaluation structure covers not only the assembly parts' geometric and physical characteristics, but also takes into account the assembly operation data. The weight of each assemblability factor is subject to change to match the real assembly environments based on expert advice. This approach was designed for general-purpose assembly evaluation, which can find wide applications in developing a knowledge-based expert system for assembly design. Compared with other methods, this method is easy to implement, gives more information to the designer, or helps to do sensitivity analysis. The approach has the flexibility to be used in various assembly methods and different environments. The developed framework can provide users with suggestions in order to improve a design of assembly and also help obtain better design ideas. The NIST OAM is being implemented within a framework dedicated to the modelling and exchange of assembly and tolerance information. The fuzzy AHP assembly evaluation approach proposed in this work will be integrated into this framework.

DISCLAIMER

No approval or endorsement of any commercial product, service or company by the National Institute of Standards and Technology is intended or implied.

REFERENCES

Abduliah, T.A., Popplewell, K., and Page, C.J. (2003), A review of the support tools for the process of assembly method selection and assembly planning, *International Journal of Production Research*, 41(11): 2391-2410

Boothroyd, G. and Dewhurst, P. (1989), Product Design for Assembly. Boothroyd Dewhurst Inc.

Boothroyd, G. and Alting, L. (1992), Design for assembly and disassembly, *Annals of the CIRP*, 41 (2): 625-636

Ben-Arieh, D. (1994), A methodology for analysis of assembly operations' difficulty, *International Journal of Production Research*, 32 (8): 1879-1895

Chan, C.K. and Tan, S.T., Generating assembly features onto split solid models, Computer-Aided Design, 2003, 35(14):1315-1336

Coma, O., Mascle, C. and Veron, P., Geometric and form feature recognition tools applied to a design for assembly methodology, Computer-Aided Design, 2003, 35(13): 1193-1210

Chang, E. and Li, X. and Schmidt, L.C., The Need for Form, Function, and Behavior-based Representations in Design, DATLab, University of Maryland, 2000

Callahan, S., Heisserman, J., Pratt, M.J. , Sriram, R. D. and Wozny, M.J., Product Modeling for Computer Integrated Design and Manufacture, A Product Representation to Support Process Automation, 285-296, Chapman and Hall, 1997

Chuang, P.T. (2001), Combining the Analytic Hierarchy Process and Quality Function Deployment for a Location Decision from a Requirement Perspective, *International Journal of Advanced Manufacturing Technology*, 18, 842-849.

de Fazio, T. L., Rhee, S. J. and Whitney, D. E. (1997), A design-specific approach Design For Assembly (DFA) for complex mechanical assemblies, *Proceedings of the IEEE International Symposium on Assembly and Task Planning*, CA, USA, pp. 152–158

Fenves, S. J. (2001), A core product model for representing design information, NISTIR 6736, NIST, Gaithersburg, MD

Hsu, W.,Lee, C.S.G. and Su, S.F. (1993), Feedback approach to design for assembly by evaluation of assembly plan, *Computer-Aided Design*, 25(7): 395-410

ISO 10303-11, Industrial automation systems and integration -- Product data representation and exchange - Part 11: Description methods: The EXPRESS language reference manual

ISO/DIS 10303-14, Industrial automation systems and integration -- Product data representation and exchange - Part 14: Description methods: The EXPRESS-X language reference manual

ISO/CD TS 10303-28, Industrial automation systems and integration -- Product data representation and exchange - Part 28: Implementation methods: XML representations of EXPRESS schemas and data

ISO/DIS 10303-41, Industrial automation systems and integration -- Product data representation and exchange - Part 41: Integrated generic resource: Fundamentals of product description and support

ISO/DIS 10303-42, Industrial automation systems and integration -- Product data representation and exchange - Part 42: Integrated generic resource: Geometric and topological representation

ISO/DIS 10303-43, Industrial automation systems and integration -- Product data representation and exchange - Part 43: Integrated generic resource: Representation structures

ISO/DIS 10303-44, Industrial automation systems and integration -- Product data representation and exchange - Part 44: Integrated generic resource: Product structure configuration

ISO/DIS 10303-47, Industrial automation systems and integration -- Product data representation and exchange - Part 47: Integrated generic resource: Shape variation tolerances

ISO/DIS 10303-48, Industrial automation systems and integration -- Product data representation and exchange - Part 48: Integrated generic resource: Form features

ISO/DIS 10303-108, Industrial automation systems and integration -- Industrial data -- Part 108: Integrated application resources: Parameterization and constraints for explicit geometric product models

ISO/DIS 10303-109, Industrial automation systems and integration -- Product data representation and exchange -- Part 109: Integrated application resource: Kinematic and geometric constraints for assembly models

ISO/CD TS 10303-203, Industrial automation systems and integration -- Product data representation and exchange -- Part 203: Application protocol: Configuration controlled 3D design of mechanical parts and assemblies

Jakiela, M.J. (1989), Intelligent suggestive CAD system, Proceedings of MIT-JSME Workshop, MIT, Cambridge, pp.411-441, USA

Jakiela, M.J. and Papalambros, P. (1989), Design and implementation of a prototype intelligent CAD system, *ASME Journal of Mechanisms, Transmission, and Automation in Design*, 111(2), pp. 252-258

Jared, G.E.M., Limage, M. G., Sherrin, I. J., and Swift, K.G. (1994), Geometric reasoning and design for manufacture, *Computer-aided Design*, 26(9): 528-536

Kim, J.S. (2003), Negotiation support in electronic commerce using fuzzy membership functions and AHP, *Proceedings of the 6th Pacific Rim International Workshop on Multi-Agents (PRIMA) 2003*, Seoul (Korea), pp.93-104.

Lee, K. and Gossard, D. C., A hierarchical data structure for representing assemblies: Part-1, CAD, 1985, 17(1): 15--19

Li, R.K. and Hwang, C.L. (1992), A framework for automatic DFA system development, *Computers in Industrial Engineering*, 22(4): 403-413

Lim, S.S., Lee, I.B.H., Lim, L.E.N., & Ngoi, B.K.A. (1995), Computer aided concurrent design of product and assembly processes: A literature review, *Journal of Design and Manufacturing*, 5(1): 67–88

Liu, T.H. and Fischer, G.W. (1994), Assembly evaluation method for PDES/STEP-based mechanical systems, *Journal of Design and Manufacturing*, 4(1): 1-19

Liu, T.H. (1992), An object-oriented assembly applications methodology for PDES/STEP based mechanical systems, *PhD Thesis*, The University of Iowa, USA

Miles, B.L. and Swift, K.G. (1992), Working together, Manufacturing Breakthrough

Miyakawa, S., Ohashi, T. and Iwata, M. (1990), The Hitachi new assemblability evaluation method, *Transactions of the North American Manufacturing Research Institute*, SME

Molloy,E., Yang, H. and Brown, J. (1991), Design for assembly with concurrent engineering, *Annals of CIRP*, 40(1): 107-110

MOKA: A Framework for structuring and representing engineering knowledge, 1999, http://www.kbe.coventry.ac.uk/moka/meta.htm

Noort, A., Hoek, G. F. M. and Bronsvoort, W. F., Integrating part and assembly modeling, Computer-Aided Design, 2002, 34(12): 899-91

Saaty, T.L. (1991), The Analytic Hierarchy Process, McGraw-Hill, New York, NY

Shah, J. J., Assessment of features technology, Computer-Aided Design, 1991, 23(5): 331-343

Shah, J. J. and Rogers, M. T., Assembly Modeling as an Extension of Feature-based Design, Research in Engineering Design,1993, 5: 218-237

Sturges,R.H. and Kilani, M.I. (1992), Towards an integrated design for an assembly evaluation and reasoning system, *Computer-Aided Design*, 24(2):67-79

Stokes, M., Managing Engineering Knowledge: MOKA Methodology for Knowledge Based Engineering Applications, American Society of Mechanical Engineers, 2001, ISBN 0791801659

Sudarsan, R., Han, Y.H., Feng, S.C., Roy, U., Wang, F., Sriram R. D., and Lyons, K. (2003), Object oriented representation of electro-mechanical assemblies using UML, NISTIR 7057, NIST, Gaithersburg, MD

Sudarsan, R., Baysal, M., Roy, U., Foufou, S., Bock, C., Eswaren, S., Lyons, K. and Sriram, R. D., Information Models for Product Representation: Core and Assembly Models, National Institute of Standards and Technology, 2004, NISTIR 7173, Gaithersburg, MD 20899, USA

Sung, R.C.W., Corney, J.R., and Clark, D.E.R. (2001), Automatic assembly feature recognition and disassembly sequence planning, Journal of Computing and Information Science in Engineering, Transactions of ASME, Vol.1, No.4, pp.291-299

Swift, K.G. (1981), Design for Assembly Handbook, Salford University Industrial Center, UK

Van der Net, A, Designing and manufacturing assemblies, Eindhoven University of Technology, 1998

van Holland W. and Bronsvoort W. F., Assembly features in modeling and planning, Robotics and Computer Integrated Manufacturing, 2000, 16(4): 277-294

Warnecke, H.J. and Bassler, R. (1988), Design for assembly - part of the design process, Annals of the CIRP, 37(1): 1-4

Whitney, D. E. and Mantripragada, R, The Datum Flow Chain: A systematic approach to assembly design and modeling, ASME Design Engineering Technical Conferences and Computers in Engineering Conference, 1998, ASME

Whitney, Daniel E. Mechanical Assemblies: Their Design, Manufacture, and Role in Product Development, Oxford University Press, 2004

Zha, X.F. and Lim, S.Y.E. (1998), Integrated knowledge-based assembly sequence planning, *International Journal of Advanced Manufacturing Technology*, 14(1): 50-64

Zha, X.F., Lim, S.Y.E., and Fok, S.C. (1999), Integrated knowledge-based approach and system for product design for assembly, *International Journal of Computer Integrated Manufacturing*, 12(3): 211-237

Zha, X.F. (2001), Neuro-fuzzy comprehensive assemblability and assembly sequence evaluation for assembly, *Artificial Intelligence for Engineering Design, Analysis, and Manufacturing*, 15(4): 367-384

Zha, X.F. (2002), Integrating the STEP-based assembly model and XML schema with the fuzzy analytic hierarchy process (AHP) for assembly evaluation, NTUIR, Singapore

Zha, X.F., and Du, H. (2002), A PDES/STEP-based model and system for concurrent integrated design and assembly planning, *Computer-Aided Design*, 34(12): 1087-1110

Zha, X.F., Sebti, F., Sudarsan, R., and Sriram, R.D. (2004), Analysis and evaluation of STEP-based electro-mechanical assemblies: an integrated fuzzy AHP approach, *Proceedings of ASME DETC 2004*, Paper No. DETC CIE-57708