Submitted to Proceedings of DETC'04
2004 ASME Design Engineering Technical Conference
September 28-October 2, 2004, Salt Lake City, Utah, USA

DETC2004/CIE-92

ANALYSIS AND EVALUATION FOR STEP-BASED ELECTRO-MECHANICAL ASSEMBILIES: AN INTEGRATED FUZZY AHP APPROACH

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ABSTRACT

Assemblability analysis and evaluation play a key role in assembly design, assembly operation analysis and assembly planning. This paper proposes 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. In the paper, two assembly representation models are first brought up and elaborated: the EXPRESS/XML schema-based model and the NIST object-oriented UML-based Open Assembly Model (OAM). These two models are then integrated together; the OAM incorporates the EXPRESS/XML schema-based assembly model to completely capture the detailed geometric information. Based on STEP, the proposed assembly evaluation approach uses the EXPRESS/XML schema-based model as the information source, and the evaluation structure covers not only the assembly parts' geometric and physical characteristics but also takes into account 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. The case study shows that the proposed approach is feasible.

1. INTRODUCTION

It has long been recognized that the decisions made during the design stages have a great impact on the total cost of a product. Design for assembly (DFA) (assemblability analysis and evaluation) 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, affecting product performance in the later stages of the product's life cycle. To design a low-cost product, designers need to know whether the designed product can be assembled and how difficulty the assemblability of its components is. Assembly evaluation is the means to recognize 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 improving design quality for better assemblability.

An effective and efficient evaluation method for assemblability should indicate the cause of design weakness by identifying the tolerances, form features, and geometries of assembly parts, rather than simply provide an evaluation score for the assembly parts or assembly operations. During the assembly design process a set of solution alternatives is

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evaluated, and a 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 comprehensive evaluation and justification to come out of a final solution from a set of alternatives determined by multiple factors or suggested by many evaluators.

This research aims to propose an integrated fuzzy AHP 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; 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.

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 on the related work of 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 lacking geometric reasoning capabilities, their system 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 will give 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 the assembly operations. This reduces the user input requirement.

Their system calculates a manufacturability index for individual components and a fitting index between the components.

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.

From the review of the related work, we can conclude that although there are some *ad hoc* methodologies and systems developed for assemblablity 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 method built by adopting the analytic hierarchy process and fuzzy set theory. 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.

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 (ISO 10303-28, 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. We integrate these two models together; the OAM incorporates the EXPRESS/XML schema based assembly model 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 NIST Core Product Model (CPM) has been developed to unify and integrate product or assembly information. The CPM 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. The Entity-Relationship data model influences the model heavily; accordingly, it consists of two sets of classes, called object and relationship, equivalent to the UML class and association class, respectively.

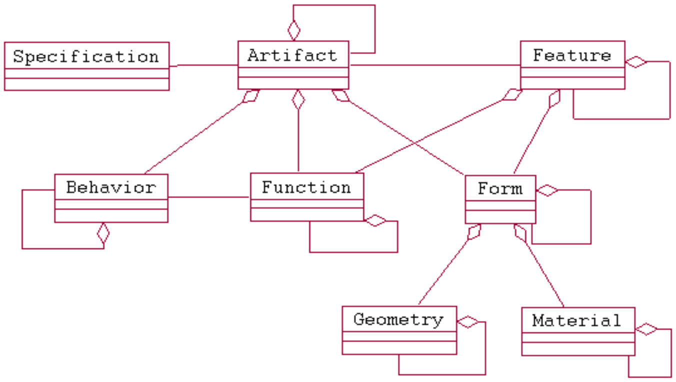

Figure 1: Entities in the Core Product Model

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 for 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.

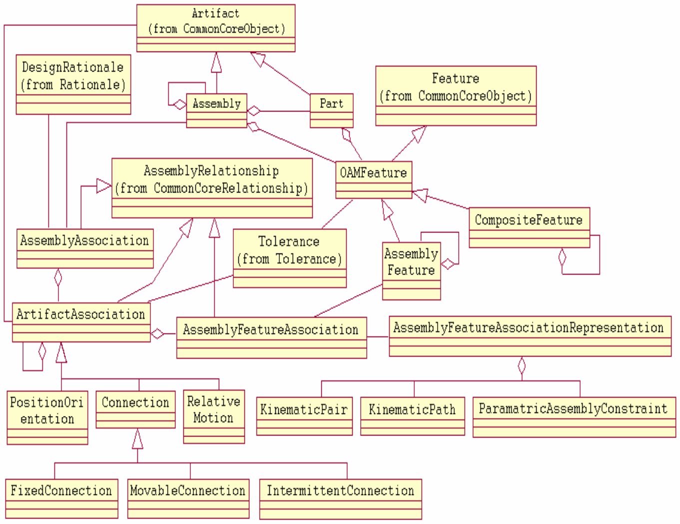

Figure 2: Main schema of Open Assembly Model

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. Assembly features are a collection of geometric entities of artifacts. They 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 The EXPRESS/XML Schema-Based Assembly Model

In the work (Zha and Du 2002), the product model based on the hierarchical assembly model consists of **Product (Assembly)**, **Subassembly**, **Part** and **Connector** objects. 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.

The entity **Assembly (Product)** 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** 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).

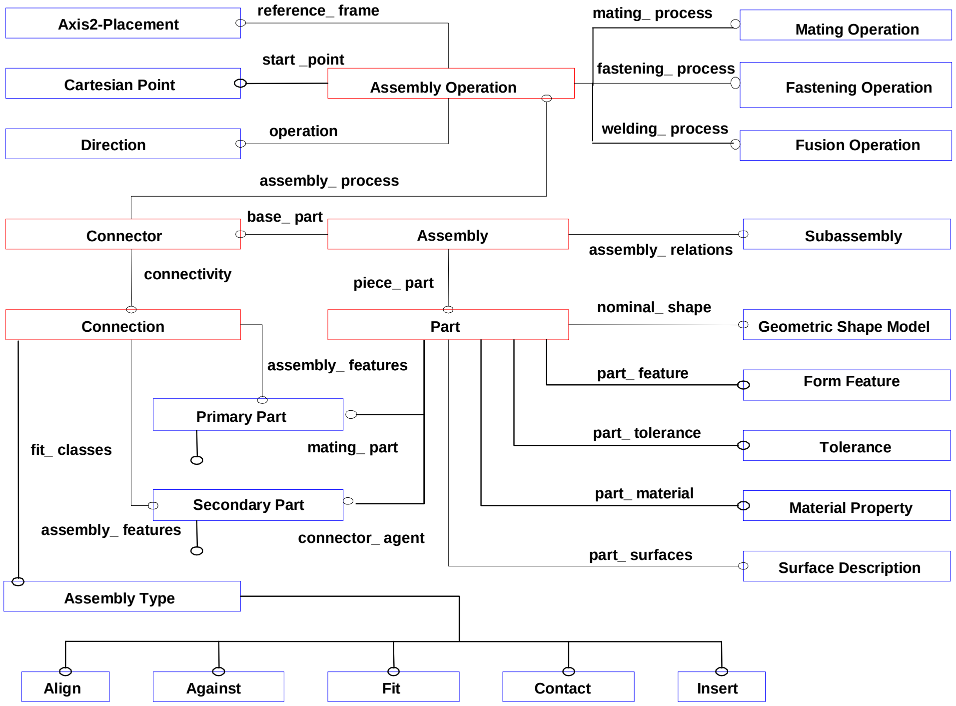

Figure 3: Assembly model in EXPRESS-G

The entity **Subassembly** is defined as the subtype of **Assembly**, so that it can inherit the attributes of **Product** without 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** should be able to provide 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 kinematic 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 list 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>
```

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.

4. FUZZY AHP APPROACH FOR ASSEMBLY EVALUATION

Due to the uncertainty and fuzziness of design specifications and technical requirement, and the above parameters with different degree of importance on the overall difficulty of assembly, it is difficult to assess the assemblability of the design using the traditional approach (Zha 2001). In this work, a method for assembly evaluation is constructed using the analytic hierarchy process (AHP) approach (Saaty 1991) to multi-order fuzzy justification and evaluation problem. In this section, we discuss in detail the fuzzy hierarchical evaluation approach for assembly difficulty.

4.1 Assemblability Factors and Weights

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

4.1.1 Assemblability Factors

Considering the STEP-based assembly model as discussed above, 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: geometry characteristics (related to parts' geometry), physical characteristics, connection characteristics (related to the type of contact between the components), and operation characteristics. They are described as an evaluation factor tree (Zha 2001). These different parameters have different degrees of importance, which means that they have different degrees of influence on the overall difficulty. The widely used methods to find the relative importance of each parameter are: pairwise comparison; block distance model; and rank reciprocal rule (Ben-Arieh 1994). In this work, the analytic hierarchy approach (Saaty 1991) 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). More details are discussed below.

4.1.2 Weight of Parameters

The acquisition of fuzzy quantities or knowledge is mainly referred to as acquiring the weights of assemblability factors. 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 amount of 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 triangular 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 required 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 in ranking 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 are 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.

4.2 Models for 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.

4.2.1 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.

$$R = \begin{array}{c} \\ \mu_1 \\ \mu_2 \\ \vdots \\ \mu_n \end{array} \begin{array}{c} \begin{array}{cccc} \nu_1 & \nu_2 & \cdots & \nu_l \end{array} \\ \begin{pmatrix} z_{11} & z_{12} & \cdots & z_{1l} \\ z_{21} & z_{22} & \cdots & z_{2l} \\ \vdots & \vdots & \cdots & \vdots \\ z_{n1} & z_{n2} & \cdots & z_{nl} \end{pmatrix} \end{array}$$

$$r = \begin{array}{c} \\ \mu_{11} \\ \mu_{12} \\ \vdots \\ \mu_{1m_1} \\ \mu_{21} \\ \mu_{22} \\ \vdots \\ \mu_{2m_2} \\ \vdots \\ \mu_{n1} \\ \mu_{n2} \\ \vdots \\ \mu_{nm_n} \end{array} \begin{array}{c} \begin{array}{cccc} \nu_1 & \nu_2 & \cdots & \nu_l \end{array} \\ \begin{pmatrix} r_{11} & r_{12} & \cdots & r_{1l} \\ r_{21} & r_{22} & \cdots & r_{2l} \\ \vdots & \vdots & \cdots & \vdots \\ \vdots & \vdots & \cdots & \vdots \\ \vdots & \vdots & \cdots & \vdots \\ \vdots & \vdots & \cdots & \vdots \\ \vdots & \vdots & \cdots & \vdots \\ \vdots & \vdots & \cdots & \vdots \\ \vdots & \vdots & \cdots & \vdots \\ \vdots & \vdots & \cdots & \vdots \\ \vdots & \vdots & \cdots & \vdots \\ \vdots & \vdots & \cdots & \vdots \\ r_{(m_1+m_2+\ldots+m_n)1} & r_{(m_1+m_2+\ldots+m_n)2} & \cdots & r_{(m_1+m_2+\ldots+m_n)l} \end{pmatrix} \end{array}$$

After carrying out the hierarchical analysis and statistics, we can obtain the percentage r_{ij} ($i = 1,\ldots,(m_1 + m_2 + \ldots + m_n)$, 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,…,n) and $u_i = (u_{ij}, j = 1,\ldots,m_i)$.

For the first-order model, the value matrix and its voting matrix are $w_i = (w_{ij}, j = 1,...,m_i)$ and r_{ij}, respectively. Based on the definition of evaluation matrix, we have

$$z_i = w_i \circ r_i \qquad (1)$$

and

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

where, $\vee$ and $\wedge$ 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 matrix and value matrix can be represented as $R = (z_i, i = 1,...,n)$ and $W = (w_i, i = 1,...,n)$ respectively. Thus, the final evaluation results are determined as follows

$$Z = W \circ R \qquad (2)$$

4.2.2 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. After the allocated difficulty scores are obtained, they can be easily used to evaluate the assemblability in design. This can be accomplished by evaluating the assemblability of a joint/connector. With respect to the STEP-based model as discussed before, 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:

$$AEI\ (J) = \frac{1}{100} \sum_{i=1}^{n} ds_i(x_i) \qquad (3)$$

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 agent(s) is used to join the mated parts. Assuming all the assembly characteristics among the mated parts and the agents are equally important, the assembly score for a fastener joint is calculated as follows:

$$AEI\ (J) = \frac{1}{100p} \sum_{j=1}^{p} \Big(\sum_{i=1}^{n} [ds_i(x_i)]_j \Big) \qquad (4)$$

where, *p* is the total number of secondary parts and agents involved in the fastener joint.

4.3 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:

$$SEI\ (S_i) = \frac{1}{100 n_i} \Big\{ \sum_{i=1}^{n_{i1}} ds_i(x_i) + \frac{1}{p} \sum_{k=1}^{p} \Big(\sum_{j=1}^{n_i - n_{i1}} [ds_j(x_j)]_k \Big) \Big\} \qquad (5)$$

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 (5), the preferred sequence is chosen as the one with the lowest sequence evaluation index.

5. INTEGRTAED ASSEMBLY EVALUATION FRAMEWORK

The integrated assembly evaluation framework is shown in Figure 4, 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.

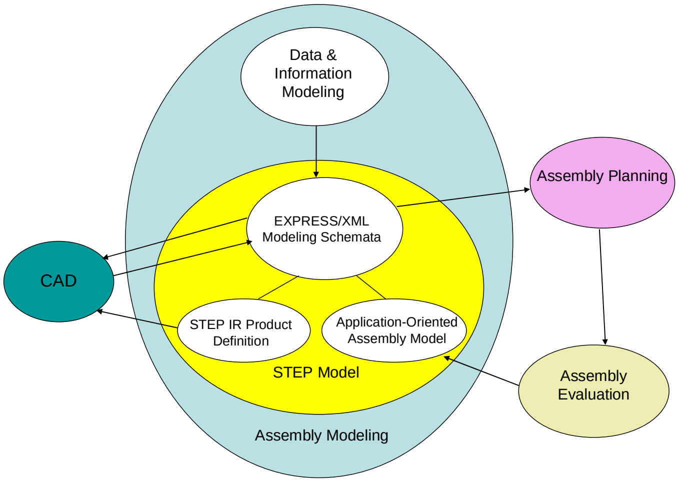

Figure 4: An overview of the framework for integrated assembly evaluation

Using feature recognition techniques, 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). 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.

6. CASE STUDY

To verify and illustrate the proposed approach, the optic lens assembly with eight parts, as shown in Figure 5, is simulated. The product consists of eight parts labeled: 1-doublet 1, 2-spacer, 3-doublet 2, 4-lock ring, and 5-subassembly 1 (composed of sp$_1$, sp$_2$, sp$_3$ and sp$_4$, and pre-assembled.) 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 accomplished by a robotic system. The assembled product is a module/subassembly to be mated into a large assembly.

As discussed above, the unified description of 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 model for the optic lens in an assembly can be thought of as consisting of the shaft 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.

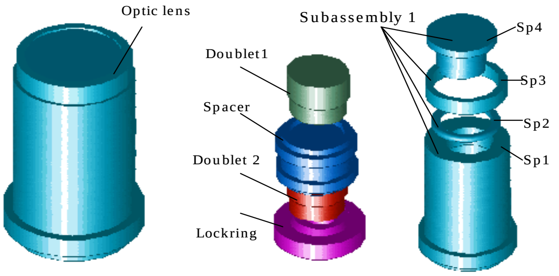

Figure 5: Optic lens assembly

All these data and information comprise the main parts of the optic lens STEP model. For example, the XML of the part lock ring can be given as follows:

```
<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 sequence requires 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 scores are 11.93 and the assemblability evaluation index (AEI) are 0.1193 (0.12). With the fuzzy hierarchical evaluation method, the evaluation result is (0.42, 0.71, 0.91), which means that the probability with medium and high assemblability are high (>=70%). Thus, the assemblability can be considered to be good.

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 constraints for linear assembly. 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

This paper presented an integrated fuzzy AHP approach to evaluating assemblability and assembly sequence for STEP-based electro-mechanical products. The STEP-based data model represented by EXPRESS/EXPRESS-G and XML schemas was used as the assembly evaluation information source. The evaluation structure covers not only the assembly parts’ geometric and physical characteristics, but also takes into account the assembly operation data necessary to assemble the parts. The weight of each assemblability factors 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. 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. Part of the work on the STEP-based assembly model and integrated assembly evaluation was done while the first author was with Nanyang Technological University and Institute of Manufacturing Technology, Singapore.

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