A Framework for the Development of Automatic DFA Method to Minimize the Number of Components and Assembly Reorientations

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Abstract. Assembly is a part of manufacturing processes that must be considered at the product design stage. Design for Assembly (DFA) is a method to evaluate product design in order to make it simpler, easier and quicker to assemble, so that assembly cost is reduced. This article discusses a framework for developing a computer-based DFA method. The method is expected to aid product designer to extract data, evaluate assembly process, and provide recommendation for the product design improvement. These three things are desirable to be performed without interactive process or user intervention, so product design evaluation process could be done automatically. Input for the proposed framework is a 3D solid engineering drawing. Product design evaluation is performed by: minimizing the number of components; generating assembly sequence alternatives; selecting the best assembly sequence based on the minimum number of assembly reorientations; and providing suggestion for design improvement.

1. Introduction

Design for Assembly (DFA) is a method to simplify the product structure, so it will reduce the assembly cost. Assembly cost reduction is achieved through reducing the assembly time of product. There are three DFA methods so far: AEM (Assembly Evaluation Method) of Hitachi, the Lucas-DFA, and the Boothroyd-Dewhurst DFA [1]. AEM and the Lucas-DFA proposed an assembly evaluation method based on values scale, the values are given as relative measure of assembly difficulties of each component. Assembly evaluation with AEM and the Lucas-DFA tends to be subjective, and these methods do not provide guidelines for design improvements.

DFA method that provides guidelines for design improvements is the DFA developed by Boothroyd and Dewhurst (BD-DFA). In this method, design efficiency is determined by considering the number of components in a product, the ease of handling, insertion and fastening [2]. This method has been widely used in manufacturing industries because it is more applicable [1,3,4,5].
Inputs for the BD-DFA are product’s engineering drawing, exploded views, and assembly sequence. These inputs are used to recognize a number of assembly features in each component of the product design, which consist of: (1) geometric assembly features, such as: basic shapes, rotational symmetry, and feature location; (2) non-geometric assembly features, usually related to the component characteristics, such as: slippery or not, flexible or not, abrasive or not, and their size (small, medium, or large); (3) operational assembly features, related to the insertion problem of component when assembled, such as: a component requires gripping or holding down before it is finally secured or not, easy to align during assembly or not, requires vertical insertion or not, and what fastener type is used.

Outputs of the BD-DFA are assembly time estimation, assembly cost, and design improvement suggestions. Based on assembly features of component, determine the assembly code to find assembly time estimation from handling and insertion time data table. Assembly cost is calculated based on this assembly time estimation. The assembly time is reduced by [2]:

1. Reducing the number of components.
2. Improving the design of components so then:
   a. Easy to grasp and manipulate.
   b. Easy to align.
   c. Easy to insertion.

The first BD-DFA was implemented manually (paper based) using given assembly sequence. Too much effort and time consuming to evaluate assembly design manually, there are some error possibilities in recognizing the assembly features and predicting the assembly time [6]. To overcome these issues, there are several software have been developed, however the developed software are still a manual technique supported by computer [6,7], because the software only used for data manipulation and data calculation, while the required data are still input by the user.

Nowadays the CAD (Computer Aided Design) system has been more sophisticated, so that there is a larger opportunity to develop an automatic DFA method, since data extraction, data manipulation and analysis, and re-design suggestions could be performed in computer based. Therefore product evaluation process and design improvement could be done easier.

2. Automatic DFA Method

Li and Hwang [8] proposed a framework for the development of automatic DFA method in CAD system base, the framework consisted of five modules, namely: assembly sequence generation, assembly features extraction, assembly codes determination, data manipulation and computation, and re-design suggestion. Each module was an evaluation step constructed based on experiences, rules, or theory in DFA methodology and it was developed as automatic DFA method. But the effort met some difficulties in developing re-design suggestion module. Soh et al [9] proposed a systematic methodology of DFA and DFD (design for disassembly) for concurrent consideration on remanufacturing perspective.

The automatic DFA method is usually manifested in software which is integrated with CAD system. Refer to the framework proposed by Li and Hwang [8], it is necessary to develop some automatic methods, namely: automatic method for assembly features extraction and assembly codes generation; automatic method for re-design suggestion, and; automatic method for assembly sequence generation.

Several researchers have discussed the development of the automatic method for assembly features extraction, and assembly codes determination: Li and Hwang [10] and Coma et al [11] used CAD drawing in B-Representation as input; while Ong et al [3] used CAD drawing in a 3D solid as input. The assembly codes are needed for assembly time estimation.

The development of automatic method for design improvement suggestion is still finding some difficulties in getting information of component function, because it usually needs non-geometric information. Mo et al [12] developed a graph model called FRM (function relation model) to analyze the function of a component. This model acquired DFA methodology into knowledge database and was
intended to support the expert system. The component function was defined by the designer in the form of graph and matrix, and then the matrix values were used as an input to evaluate the product design in order to have a simpler structure. The model proposed by Mo et al [12] could be categorized as semi-automatic method, since there were still have some evaluation process that could not be done automatically.

Li and Hwang [8] proposed a framework based on the Boothroyd-Dewhurst DFA, while Dalgleish et al [7] proposed a framework based on the Lucas DFA called the Sandpit DFA. Lee et al [13] proposed an automatic DFA method based on DFA methodology in general, this framework was developed for INSPIRE (intelligent assembly planning integrated with redesign) which integrated the assembly planning and the design improvement. INSPIRE have interactive process with designer to meet the information needs in analysis. This interactive process is facilitated by an interface called RIC (revenge input constructor).

3. Proposed Framework for Automatic DFA Development

This article proposes a framework for the development of automatic DFA method that refer to product design evaluation steps in the Boothroyd-Dewhurst DFA methodology, namely [2]:

1. Minimize the number of component
2. Improve the assembly features of product design

This framework considers the assembly sequence problem in design improvement. The required data for product design evaluation are extracted automatically from the CAD system by using a 3D solid drawing as input. Design evaluation is performed by evaluating the basic function, assistant function [12] and assembly features of each component.

Product design evaluation is started by minimizing the number of components of a product. A component at the end position in assembly is usually supported by a number of other components that are assembled with it. If a component moves when the product is operated, then supporting components also move along with it. This set of mutually supportive components is defined as group in this paper. Grouping of product’s components results the category of each component, i.e. main component or supporting component. Further, each component’s group is examined to know the effect of removing one or a number of supporting component to the degree of freedom of the group.

Each supporting component is tried to be removed (reduction or elimination) from product structure by determining the function of components on its group first. The function of a component means the role of a component at the end position to support other components. The component function criteria proposed in this article refer to the criteria proposed by Mo et al [12]:

1. Cooperative is if a number of components support each other in performing the same function.
2. Independent is if a component has a function independently.
3. Compound is if a component performs more than one function simultaneously.
4. Transitional is if a number of components perform one function serially.
5. Redundant is if a number of components perform a same function independently.

Mo et al [12] recommended designing a component to have compound classification, the component which has the classification function of cooperative, transitional, or redundant become the candidates to be removed from the product structure. The framework in this article uses a technique to determine the classification of component function based on the degree of freedom of component and the group of components.

The output of component grouping analysis is the information of main component and supporting components, while the output of the component function analysis is recommendation for reduction or elimination of component. Reduction means transferring the function of several components into one component, so that the amount of components could be reduced. Elimination means removing a component from product structure without transferring it functions to other component. Elimination is suggested to be done only for supporting component.
The evaluation of product design, as an effort to provide some suggestions for design improvement, could be conducted through four steps, namely:

1. Grouping the components to identify the main component and the supporting component.
2. Determine the value of degree of freedom in each group of components.
3. Determine the classifications of component function in the product.
4. Provide suggestion for reduction or elimination of component to minimize the number of components in the product.

BD-DFA has not yet discussed about assembly sequence and its effect to the product design, whereas DFA method requires assembly sequence to estimate assembly time. The framework proposed in this article considers the assembly sequence problem in identifying the component features that need to be improved, so that total assembly reorientation during assembly operation could be minimized. In DFA methodology, minimizing the number of assembly reorientations and minimizing the number of components are the efforts for assembly time reduction.

The BD-DFA provides some suggestions for reducing the assembly time of product. These suggestions are based on handling and insertion problem. The suggestions, for example, related to the symmetrical problem for easier handling, or the fillet for easier insertion. Assembly sequence analysis, handling and insertion analysis in product assembly evaluation processes could be done independently, so that it could be considered separately. This research will not discuss handling and insertion issues in features improvement, besides this problem could be considered independently, it has also been well defined in the BD-DFA.

The evaluation of product design involving the assembly sequence analysis is conducted by generating assembly sequences firstly. The feasible assembly sequences are generated by considering the precedence constraints and the component regions. The precedence constraints in this research, related to the geometric constraints, are generated based on the information of collision free path of assembly. The collision is a condition if a component blocked by other components when assembled. The region is a condition if the assembly sequence of product could be randomized without breaking the precedence constraints. Some assembly sequence alternatives could be generated by considering the region. The product design evaluation involving assembly sequence analysis could be done through the following steps:

1. Detect the collision free path of assembly component.
2. Generate the assembly precedence based on the information of collision free path of each assembly component.
3. Determine the region of each component of product.
4. Generate the feasible assembly sequence alternatives.

If some assembly sequence alternatives have been obtained, then select the best one. The best alternative is selected based on the minimum number of assembly reorientations of all assembly sequence alternatives must be calculated. If the minimum number of reorientations is more than once and successively, then it is suggested to improve the features of assembly component. These suggestions could be used by the designer but this research does not discuss how the feature improvement is done. This task really depends on the designer experiences. The assembly reorientation analysis could be conducted with the following steps:

1. Select the best assembly sequence based on the minimum number of assembly reorientation.
2. Check the assembly reorientation condition during assembly operations (more than once reorientation and successive or not).
3. Provide re-design suggestions for minimizing the number of assembly reorientations.

Design evaluation process could be done repeatedly until the designer feel confident that the product design already has a minimum number of components, a minimum number of assembly reorientations and the product could be functioned correspond to the design objective.
The proposed framework consists of three parts of model development, namely: the model for minimizing the number of product components, the model for analyzing assembly sequence, and the model for minimizing the number of assembly reorientations, see Figure 1. The model here is defined as criteria, propositions, rules and algorithms. The required information is extracted from CAD system database, and stored in Component Database.

![Diagram](image)

Figure 1. Framework for automatic DFA method development

### 3.1 Geometric data extraction model

The first stage in realizing automatic DFA method is the development of geometric data extraction model. Data are extracted from CAD database using an algorithm called Component Geometric Data Extraction Algorithm, this algorithm has been developed and published by Alfadhlan et al [14] as part of this research. The extracted data consist of: mate type, contacting point coordinate, normal vector, and volume of component. These data will be stored in Component Database.

### 3.2 The number of components analysis model

The second stage in the framework is the development of a model for analyzing the number of components. Output of this analysis is suggestions for minimizing the number of components. Analysis task is performed through three steps, namely: grouping the component to identify the main components...
and supporting components, determining the degree of freedom (DOF) of component’s group, and determining the function of supporting components.

Component grouping is determined by considering mating condition information, this information indicates the connections between components, components in a group will be connected each other. The category of components could be determined based on the number of connections, the main component is determined among components in a group with the largest connections. If there is more than one component with the largest number of connections, then all that components are defined as main components. The supporting components are all other components that are not defined as main component. It is necessary to develop an algorithm called Component Grouping Algorithm for analyzing the category of components. Input for this algorithm is mate type information of component, while it outputs are component’s group, mating list of each group, and components category. These outputs are stored in Group Components Database.

The automatic DFA in this study is developed to have ability to identify the candidate of components that can be reduced or eliminated automatically. The candidates are identified by considering component function classifications. Component function is defined using the degree of freedom of components and group of components. To analyze the function of components, it is needed to develop the algorithm of group’s degree of freedom determination. Inputs for this algorithm are component’s group, mate type, contacting point coordinates, and normal vector of component’s contacting face. While component function classification and identification of component candidate, for reduction or elimination, are determined using the algorithm of component function determination. Inputs for this algorithm are degree of freedom of component’s group, mate type, and normal vector of component’s contacting face.

3.3 Assembly sequence analysis model

The third stage in the proposed framework is the assembly sequence analysis model. This analysis is performed through four steps, namely: collision detection of assembly free path, precedence constraint generation, component region determination, and feasible assembly sequence generation. Assembly collision free path of component is specified based on information of mate type and normal vector direction. Mating indicate a connection, while normal vector indicate blocking path of a component by other components when assembled. An algorithm for detecting assembly collision free path need to be developed, this algorithm called Component Collision Detection. Inputs for this algorithm are mate type and normal vector information. Output of this algorithm is assembly collision free path of each component. This information is stored in Collision Free Path Database. The algorithm of Component Collision Free Path has been developed and published by Alfadhlani et al [14].

If information of assembly collision free path has been obtained, then precedence constraints of assembly could be generated by examining the information of assembly collision free path to disassemble each component. Disassembly approach is used because the information of assembly collision free path only shows the assembly path of final component that can be assembled in particular stage. Because of this approach, the direction of assembly collision free path should be changed in opposite way to obtain disassembly collision free path. After disassemble each component, update the information of assembly collision free path without taking into account the removed components.

The component candidate to be removed is determined based on the information of assembly collision free path. The priority of component to be removed, among candidates, is determined based on criteria: (1) the minimum number of connection among the candidates and the component that has not been selected; (2) component candidate with a minimum volume. Precedence constraints contain the information of component’s predecessor, predecessor a component are all components that have been removed previously and connected with it. To generate precedence constraints, develop the algorithm of Precedence Constraint Generation. Inputs for this algorithm are information of assembly collision free path, and volume of component.
Region information is used to find assembly sequence combination without breaking the precedence constraints. To determine region of components, develop the algorithm of Component’s Region Determination, input for this algorithm is precedence constraints information. If precedence constraints and region information have been determined, then several alternatives of feasible assembly sequences could be generated. The assembly sequence are generated using the algorithm of Assembly Sequence Generation, input of this algorithm are precedence constraints and region of component. Precedence constraint information contains complete information of component’s predecessor, but does not have the information of component’s successor. Because of that, this precedence constraint could not be used directly to determine the component will be assembled next after a component is assembled. To get the explanation of this problem, then use the algorithm of Precedence Relation Determination.

To support Assembly Sequence Algorithm, it is required one step preparation to find all assembly sequence combinations from initial assembly sequence. This step is developed in the algorithm of Assembly Sequence Combination Determination. The algorithm of Precedence Relation Determination and the algorithm of Assembly Sequence Combination Determination are supporting algorithm, so both of these algorithms are not shown in Fig. 1.

3.4 Assembly reorientation analysis model
Re-design suggestions for the design improvement need to be provided in order to make the product could be assembled easier by minimizing the number of component and assembly reorientation. The number of assembly reorientation is analyzed by calculating the number of reorientation required in each alternative of assembly sequences generated, and then select the best alternative which has the minimum number of assembly reorientation. The number of assembly reorientation is attempted to be more minimum through improving the features of assembly component.

It needs to develop the algorithm of Assembly Sequence Selection for: analyzing and calculating the number of assembly reorientation on each assembly sequence alternatives; and selecting the best alternative. Inputs for this algorithm are assembly collision free path, and assembly sequence alternatives. While the Re-design Suggestion Algorithm needs to be developed to provide re-design suggestions, inputs for this algorithm are selected assembly sequence, and the number of its assembly reorientation.

4. Conclusion
This article discusses a framework proposed for developing automatic Design for Assembly (DFA) on CAD system base using a 3D solid drawing as input. This DFA method is addressed for design evaluation and re-designs suggestions, through: (1) reducing or eliminating or maintaining the current number of product components; and (2) minimizing the number of assembly reorientation. Re-design suggestion is provided for simplifying product structure and ease of assembly.

This effort is performed through three general steps: first, defining components function; second, identifying components which could be reduced or eliminated based on geometric information; third, generating assembly sequences and selecting the best one. Some parts of this research that are: the algorithm of Component Geometric Data Extraction, and the algorithm of Collision Detection, have been developed and published, while other parts are being developed.

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