INCREASING THE EFFICIENCY OF MANUFACTURING PROCESSES USING DESIGN-FOR-ASSEMBLY TECHNIQUES

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Abstract

The efficiency of manufacturing processes can be increased if modular products are designed to be easily configured during assembly. This paper describes an approach that attempts to define a modular architecture in order to improve assembly by producing the product assembly sequence during the design phase. It optimizes the design-for-assembly approach by considering the role of different flows in the modular product structure. A case study demonstrates the approach.

Keywords: modular, design, assembly, manufacture.

Introduction

Design-for-assembly is becoming a well-used technique [1]. It can reduce manufacturing and assembly costs and provide other benefits [2]. One well known technique is that of Boothroyd and Dewhurst [3]. That method measures the complexity of assembly to produce a quantitative result [4] by considering the shape of the part, connections and manual handling operations. It computes time and cost, and suggests part-to-part assembly difficulties and possible reductions in the number of parts or the merger of parts, and the simplification of assembly operations. The method is protracted and arduous and often needs a detailed product design or existing product or prototype. By contrast, Stone and McAdams [5] start from a definition of the functional structure of a product before analyzing how easy a product is to assemble. Design-for-assembly techniques can then be applied during the conceptual design phase when decisions affect production costs. The main aim was to reduce assembly time by reducing the number of components (without using detailed product models). The method could only be applied if modular products were faced [6] so that each sub-assembly or component can be unequivocally linked to a specific sub-function. The method achieved some good results compared to "Boothroyd and Dewhurst" but had two main drawbacks: a lack of identification of an efficient assembly sequence or the spatial module layout to define product architectures.

Modularity and configurability should be considered when new products are being created. Industry tends to go through many iterations and much design effort in an attempt to modularize products. This paper describes an attempt to improve the assembly of modular products by taking into account functional modules and their interactions. In this way it may be possible to achieve a product assembly sequence and so estimate assembly time. The functional analysis reported in Pahl and Beitz [7] is used. The product is seen as a set of functions and sub-functions interlaced by flows of energy, material and signals. Modules can be recognized using heuristics [5]. Starting from this, it is possible to analyze flows between modules; the results allow the identification of an accurate product structure where assembly is made easier and a sequence of assembly can be suggested. The analysis examines the number of module interfaces and typologies. The functional representation is rearranged in order to simplify flow paths. The new layout can be used to convert modules into physical structures so that it is possible to assemble the new product quickly with simple operations. The last operation is conversion from the physical product to the assembly plan.

In this paper, the method is described after a brief review of the research background. In order to show the approach a simple case study is also described. A product is redesigned and results are compared with previous design solutions and with other methods.

Design-for-assembly methods

Design-for-assembly gives a designer a thought process and guidance to develop a product in a way that also considers assembly [8] and that supports the designer in making design decisions. It often recommends logical procedures that re-use components and identify problems. Design-for-assembly was formalized as a theory thanks to "Boothroyd and Dewhurst". It can be especially useful if used during the early stages of design since it can influence costs [9]. Traditional design-for-assembly methods are used during later design phases. Some of the first design-for-assembly methods were developed in the 1980s: the "Hitachi Assembly Reliability Evaluation Method", "Lucas method" and "Boothroyd and Dewhurst method". Hitachi aimed to detect faults which might be generated when many parts are assembled together [10]. The method used two principal indicators: an assemblablity evaluation ratio which assessed design quality by determining the difficulty of operations, and an assembly cost ratio which gave elements of assembly costs [11]. A total score was evaluated as the sum of the single scores and was divided on the basis of the number of elements. The achieved value shows the assemblability ranking. The Hitachi method considers both costs and quality so that a low cost design was not necessarily considered to be the best [11]. The Lucas method is based on a point scale which gave a relative measure of assembly difficulty [12]. That method was based on three separate and sequential analyses: functional, feeding and fitting analysis. For each analysis, three indices were given which determined the designer's choice. Each assembly parameter was estimated. The last part of the Lucas method was to calculate the manufacturing cost of each component. That cost could an influence the choice of material and the manufacturing process [11]. Boothroyd and Dewhurst formulated the most widespread quantitative design-for-assembly methodology that focused on redesign rather than initial prototyping. They presented a two-step procedure. The first step evaluated each part to determine if it was strictly required or whether it was possible to eliminate or combine with other parts. The second step estimated the time taken to grasp, manipulate and insert the part during assembly. The two steps were combined to give an efficiency rating. An index was used in order to compare different assembly solutions. An improvement to the method was proposed by Stone and McAdams [5]. They defined a conceptual design-for-assembly method that used two concepts: a functional basis and module heuristics [6]. The functional basis was used to derive a functional model of a product and the module heuristics were applied to the functional model to identify a modular structure [13]. Such architecture could be used as a reference to obtain an easy-to-assemble solution. Each functional module could become an assembly module. The product could be considered completely modular when the physical embodiment could be correlated with a one-to-one mapping to functional modules, otherwise it was considered only partially modular. The degree of modularity could be used to classify a product typology [14]; an index which compares real modules with theoretical functional-based modules. The Stone and McAdams approach focused on products with a high degree of modularity. Flows of material, energy and signal were transformed by a "black box" [7] representing the main function of the product. The main function was divided into sub-functions and a complex tree structure was created. The lowest level of the structure was used to identify modules by adopting the cited heuristics.

Proposed new method

The method starts by analyzing product structure and produces an assembly sequence. A list of connections and typologies between components is required from the conceptual design phase

Product architecture. Ulrich [16] defines product architecture as the:

- Arrangement of functional elements.
- Mapping from functional element to physical component.
- Specification of the interfaces among interacting physical components.

There is no mathematical rule to identify the correct position of components in an assembled product but there are algorithms and numerical methods which enable a possible assembly sequence to be generated [16]. In design-for-assembly both the assembly sequence and the position of the components are important. The first has an impact on the second; poor architecture can affect assembly time. Two types of products were defined depending on the physical layout: Linear and Complex.

Linear products are a subclass of complex products where the product architecture is characterized by a linear arrangement of modules. In complex products the architecture is a set of modules connected in a more articulated manner. The type and number of interfaces become essential to characterize the architecture. Modules which form the product require a precise spatial layout.

Interface type and priority. A functional structure is defined to describe relationships between modules (that is interfaces) so as to generate a suitable final structure. This determines connections, interactions and machining for components. All these features need to be guaranteed for the assembly process. Interface priorities are necessary to establish which module has to be directly assembled with another, or which modules can be assembled with bridging components.

The modular product architecture is determined by using the number of interfaces between modules and the related priorities. For example, a module with a lot of interfaces is given a more central position. Then the assembly sequence continues with the other modules connected on the basis of their priority. If modules with different priority values need to be assembled with another module, the module which has a lower interface priority can be sequentially connected using bridging elements.

Assembly sequence. An assembly sequence structures the connection between components. A liaison-graph is produced from the assembly sequence. It is structured in levels. The graph comes from the product architecture representation and from the evaluation of the number and typology of the interfaces between different modules. Modules with many connections could become sub-assemblies. There are some typical methods for assembly sequence generation such as rule-based [17], part tree [18] and knowledge-based [1].

The assembly graph can represent assembly relationships, including sub-assembly, assembly sequence and joining methods and is important as different part sequences can affect the cost and efficiency of assembly.

Description of the new method. The five steps are:

- ***Modules***. Determine the number of modules using functional analysis to identify a product and the associated flows. From this, assign components to modules.

- ***Interfaces***. Modules are connected by interfaces of varying number and / or type (mechanical, electrical etc) that are defined by their input and output flows. Position and connections do not need to be decided. Typology needs to be considered. The priority of a connection allows the number and physical layout of the modules to be determined. High priority interfaces require a linear sequence of assembly and their architecture is unique. Modules which have lower priority interfaces can be connected directly if there are no other interfaces with higher priority. Otherwise it is necessary to introduce bridging elements to provide connection.

- ***Structure***. Product structure is generated based on the number of connections and their types and it determines the assembly sequence by giving modules with a high number of interfaces a more central position and giving modules with fewer interfaces a more peripheral position. The result is a structure where the core is the module with the highest number of interfaces and highest priority, surrounded by modules with lower numbers of interfaces and a lower priority.

- ***Assembly***. Assembly is achieved by merging the product structure and the interfaces. Peripheral modules with one or few interfaces generate the first level of a graph. Other modules with many connections may become sub-assemblies in the same level. The type of connection between modules is identified.

- ***Components***. This uses the flows identified earlier in the process and the technologies for making components. This information allows the following to be determined: material, shape and geometry and production processes. Components can be modified using the Boothroyd and Dewhurst method. Some rules must be detailed to easily assemble the product parts after determining the number of parts and the connections and structure.

Case study: Air vent extractor

Air vent extractors remove humid and dirty air. They are mass produced and that allows the advantages of using the method proposed in this paper to be evaluated and compared. The original model considered here had 41 components. The assembly line started from individual components to generate larger subassemblies. These sub-assembly modules converged on a main assembly line where they were finally assembled. The total assembly time was 589 seconds. The main steps of the method and the results are reported:

Modules. The modular analysis of the air vent extractor produced 6 modules with complete modularity. The number of functional modules was determined using functional analysis to identify associated flows. From this, components were assigned to modules. Heuristics were applied to identify modules.

Interfaces. Modules were connected by interfaces that were defined by their input and output flows. High priority interfaces were allocated a linear sequence of assembly. The number of interfaces, as well as their nature, was determined by the associated flows. In the vent extractor there were only mechanical and electrical interfaces. The mechanical interfaces had a higher priority than the electric interfaces. When two modules had the same number of interfaces, the module with the most Mechanical Interfaces was allocated a more central position.

Structure. Modules with a high number of interfaces were given a more central position and modules with one (or few) interfaces were placed into a more peripheral position. The result was a structure where the core was the module with the highest number of interfaces.

Assembly. The structure and the interfaces were merged. Two modules that had more than three connections become sub-assemblies. The type of connection between modules was identified. Four levels in the assembly line were identified.

Components. This used the flows identified earlier in the process and allowed determination of: material, shape and geometry and production processes. The generation of components from the modules in the conceptual phase followed the rules of Stone and Wood [6]. A detailed list of components was produced. Important solutions were focused on critical modules such as the electrical fan system.

Comparison with other methods

The vent extractor was analyzed using the Boothroyd and Dewhurst methodology obtaining an initial satisfactory result with a reduction in assembly time of 15%. A further analysis was performed with the conceptual design-for-assembly method proposed by Stone and McAdams. Finally, the new method was applied starting with the conceptual model and establishing the product structure based on the interfaces and connection types. The new method described in this paper improved the assembly time (9% lower) and the number of components (13% lower). The most significant improvement was in the electrical fan system module. This module was in a central position and connected with quick (snap-fit) systems which improved the time and ease of assembly. The connection system also improved module disassembly, especially for maintenance.

Conclusion

The approach proposed by Stone and McAdams is well structured but does not discuss potential structures. For complex industrial products, this aspect can be established on the basis of simple priority rules to connect modules. The new method starts from modular analysis and by assessing the number and type of connections between modules. The method places modules to optimize the assembly process by analyzing the product structure. The results of the new method could make well structured and organized products with a minimum number of components.

The case study is an example of the improvement achieved in the assembly of product through a reduction in the number of components. Future work will examine the application of this method to products which are not modular.

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