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A key components-based heuristic modular product design approach to reduce product assembly cost

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A Key Components-Based Heuristic Modular Product Design Approach to Reduce Product Assembly Cost

Abstract

Nowadays, increasing awareness of sustainability and varied customer requirements have driven manufacturers to reconsider product development starting from the design phase. As one response to these concerns, modular product design (MPD) has attracted significant attention. Since the architecture of a product or a system can have implications on its assembly cost, MPD and product assembly should be investigated jointly. In this paper, a heuristic clustering algorithm with key components emphasis that will reduce assembly cost is offered to group components into modules. Key product/system components are those that afford competitiveness to a company. An MPD method that can decrease product assembly cost while accommodating key components strategically is the primary motivation for this research. Upon the foundation of extant works, we provide the details of the proposed methodology and illustrate its use via a coffee maker case study.

Key Words: Modular Product Design, Heuristic Search, Key Components, Product Assembly, Reduce Cost

1. Introduction

One of the common ways to reduce complexity in a larger product or system is segmenting it into smaller subsystems. By applying this philosophy inversely to design engineering, MPD has evolved. Steward (1965), who proposed the philosophy of system partition and testing, can be considered to propose the core idea of MPD. The MPD involves clustering simple and relevant product parts into more complex and larger subassemblies (called module), and then combining these subassemblies to create a complete product. In modular product architecture, each functional product component is implemented in one subassembly (or module), with few interactions between subassemblies (Ulrich & Eppinger, 2000). Many practical advantages of MPD have been explored in recent research. For example, MPD has been shown to increase manufacturing efficiency and effectiveness (Okudan Kremer et al., 2013; Ma & Kremer, 2015); it can benefit the supply chain by reducing inventory cost and lead time (Ernst & Kamrad, 2000; Feitzinger & Lee, 1997; Kamrani & Nasr, 2008). It can also satisfy the demand for mass customization through practical and economical ways of increasing the set of product variants (Gershenson et al., 2003, 2004; Lau et al., 2007; Ma & Kremer, 2016).

Assembly consideration in the design stage (a.k.a. design for assembly (DFA)), is a systematic process that primarily concentrates on reducing the assembly costs of a product in the design stage. DFA provides quantitative methods to evaluate cost and manufacturability during the design stage, and thereby provides suggestions for cost reduction. Many products have potential cost efficiencies as low as 20% before DFA analysis is implemented, and after DFA they achieve efficiencies higher than 70% (Tatikonda, 1994). DFA methods are developed under the assumption that the manufacturing/assembly costs are set in the design stage, before any manufacturing system analysis and tooling development are undertaken (Boothroyd & Dewhurst, 1990; Nevins & Whitney, 1989). MPD can improve assembly performance (Okudan Kremer et al., 2013; Salonitis, 2014). Modular design tends to have fewer components for assembly; by increasing pre-assembly and using common interfaces, modularity decreases the cost of assembly (Fukushima et al., 2012). Implementation of DFA in design engineering could reduce unit costs, shorten manufacturing lead times and increase reliability (Boothroyd & Dewhurst, 1990; Tatikonda, 1994; Warnecke & Babler, 1988). In our research, we propose an MPD method to reduce assembly cost.

Key components of a product carry core technologies of the manufacturer (e.g., Intel's CPU); they may also have the largest sustainability influence due to cost, environmental impact, or labor-time requirements (e.g., frame of bicycle). Key components represent key competence, and the quality of key components directly determines the entire product performance. Therefore, integration of MPD, product assembly cost reduction and key components module assignment at the design stage might have several positive outcomes. To the best of our knowledge, however, existing modularity methods do not address these issues simultaneously. Accordingly, developing an MPD method, which incorporates key components specification and product assembly, is the primary motivation for this research. Below, we present a summary of the pertinent research before discussing the method we propose.

2. Literature Review

MPD is a widely-applied methodology in design engineering, and many MPD methods have evolved over decades. We summarize some of the traditional MPD methods according to their categories (i.e., Matrix-Function classification and Cluster-Graph-Math-Artificial-Genetic (CGMAG) classification).

Zhang and Gershenson (2003) introduced the matrix-function classification. Matrix methods sort components into product modules according to matrix characteristics, while function-based methods rely on intrinsic features of the complicated product/system to identify functions and form modules. Among matrix-based MPD methods, Kusiak and Wang (1993) developed the triangularization algorithm based on depth-first search and applied it along with a decoupling algorithm to generate and optimize product modules. Pimmler and Eppinger (1994) adopted a heuristic swapping algorithm to measure interaction among components in a module using five different integers. They divided the interaction into four types, and represented these types in single entries with four numbers. Newcomb et al. (1996) defined two indexes: CR (Correspondence Ratio) and CI (Cluster Independence) to measure modularity; they then applied a cluster identification algorithm to re-design products.

Among function-based MPD methods, Ishii et al. (1995) defined a fishbone diagram to represent the relationship among modules. Marshall et al. (1998) checked the match-ability between corporate goals and product requirements in the modular design. Stone et al. (1998) modified a function structure diagram to identify dominant flows, branching flows and conversion transmission flows, where each flow is a potential module or module type.

The matrix-based MPD methods focus on the similarities and differences among components, but these methods neglect the functional relationships among modules (Gu et al., 1997; Huang & Kusiak, 1998; Kusiak & Chow, 1987; Kusiak & Wang, 1993; Newcomb et al., 1996; Pimmler & Eppinger, 1994). On the contrary, function-based MPD methods emphasize functional or group relations while mostly ignoring component-level properties (Ishii et al., 1995; Marshall et al., 1998; Stone et al., 1998). To the best of our knowledge, no method has considered these two factors simultaneously.

Jose and Tollenaere (2005) divided MPD methods into five groups: (1) clustering methods, (2) graph and matrix partitioning methods, (3) mathematical programming methods, (4) artificial intelligence methods, and (5) genetic algorithms and heuristics. Herein, we refer to this categorization as CGMAG, using the first letter of each group.

Clustering methods categorize components into groups according to similarities and differences based on different design criteria (Chung et al., 2013; Ma & Kremer, 2015; Kusiak & Chow, 1987). Graph and matrix partitioning methods implement graph or matrix-based methods to sort components (Huang & Kusiak, 1998; Kumar & Chandrasekharan, 1990). Most matrix-based methods can be categorized into this group. Mathematical programming methods are used to form component groups. Kusiak and Wang (1993) presented a linear programming-based algorithm to generate modules. Artificial intelligence, a branch of computer science, is also a useful tool for clustering components. Zhang et al. (2005) discussed an evolving knowledge-based artificial intelligence technique for the modularization of components. Genetic algorithms and heuristics are among the widely used methods to solve optimization problems. Kreng and Lee (2004) proposed an MPD method that uses nonlinear programming to construct an objective function that is subject to certain constraints, and then applied a grouping genetic algorithm heuristic to search for an optimal or near-optimal modular design.

MPD is used as a tool for DFA. Assembly accounts for between 40% and 60% of the overall production time (Andeasen, 1983). The DFA is a concept of increasing ease of assembly; it serves a critical role in re-designing/re-engineering the existing products and in supporting the effectiveness and efficiency of new products' design and development (Tatikonda, 1994). The emphasis on integrated needs of managers and engineers from both manufacturing and design engineering fields provides better understanding of DFA and related tools (Rosenthal & Tatikonda, 1992).

Boothroyd et al. (1982) proposed a Product Design for Assembly manual considering handling time, geometries, insertion time and theoretical minimum of parts in assembly. The manual is composed of a step-by-step approach that includes the selection of the assembly methods (e.g., manual, high-speed automatic and robot assembly), and design analysis using a Design for Assembly Worksheet. Due to this influential work, Boothroyd and his colleagues are regarded as pioneers of the DFA technique (Lefever & Wood, 1996). Based on their manual and the research direction, several researchers contributed to DFA knowledge base (e.g., De Fazio & Whitney, 1987; Ishii et al., 1995; Lee et al., 1993).

There are other DFA developments beyond the direction of Product Design for Assembly manual by Boothroyd and his colleagues. Warnecke and Babler (1988) developed the Assembly Oriented Design Process (AODP) from four aspects of new product development, including the product structure, sub-assemblies, components, and joining techniques. The AODP integrates design rules and assembly suitability to reduce the design focused iterative loops and increase effectiveness in the design phase. Boothroyd (1994) explored Hitachi Assembly Evaluation Method (AEM) further, and pointed out that this method follows the "one motion for one part" rule. AEM provides two indices, evaluation score (E) and assembly cost ratio (K), for the measurement of assembly difficulty and product structure assembly cost, respectively. AEM has been used to evaluate the current assembly methods and provide suggestions to new product development. Several methods have been proposed to measure assembly time based on AEM (e.g., Miller et al., 2014; Mohd Naim, 2009; Owensby & Summers, 2014).

A key component may represent a core technology and thus affect the product function performance, such as the turbocharger in an automobile engine (Micheletti, 1988); or such key components may be expensive or complicated to assemble or pollute the environment and consequently influence product market performance (e.g., the cabinet of a refrigerator (Umeda et al. 2000). However, to the best of our knowledge, only one paper partially alludes to the idea of emphasizing key components during product design. Specifically, Huang and Kusiak (1998) provided a decomposition approach to cluster product components. Besides physical interactions among components, they took designers' preferences/willingness into account in module forming. They measured the willingness level of grouping two components into the same module, and used "a, e, o, u" to represent the willingness [levels] of "strongly desired, desired, strongly undesired and undesired". Key components could be handled using the concept of willingness to include in the same module. For instance, by using this method, key components and corresponding preferred components might be grouped into same modules based on designers' perception of appropriateness (i.e., "strongly desired" or "desired", "strongly undesired" or "undesired"). However, Huang and Kusiak (1998) only considered subjective preferences in key component handling; a more comprehensive and systematic approach is needed. Therefore, in this paper, in an effort to fill this gap, we propose a key components-focused MPD that considers the product assembly cost reduction as a major goal.

3. Methodology

DFA is important in product development. Stienstra (2014) summarized ten DFA principles: 1) minimize part count; 2) design parts with self-locating features; 3) design parts with self-fastening features; 4) minimize reorientation of parts during assembly; 5) design parts for retrieval, handling and insertion; 6) emphasize "top-down" assemblies; 7) standardize parts; 8) encourage modular design; 9) design for a base part to locate other components; and 10) design for component symmetry for insertion. Most DFA methods follow, or at least partially follow, these principles. In our proposed method, we intend to primarily reduce assembly cost by adopting MPD.

In the proposed methodology, clients or manufacturers will determine the quantity of key components based on expert opinion/perception or company policy. According to this pre-determined input, we select top most costly components as key components and separate them into individual modules. By applying our proposed approach, the key-component based heuristic MPD method, we group non-key components into key component modules, and calculate the assembly cost. Fig. 1 shows the steps of the proposed MPD method.

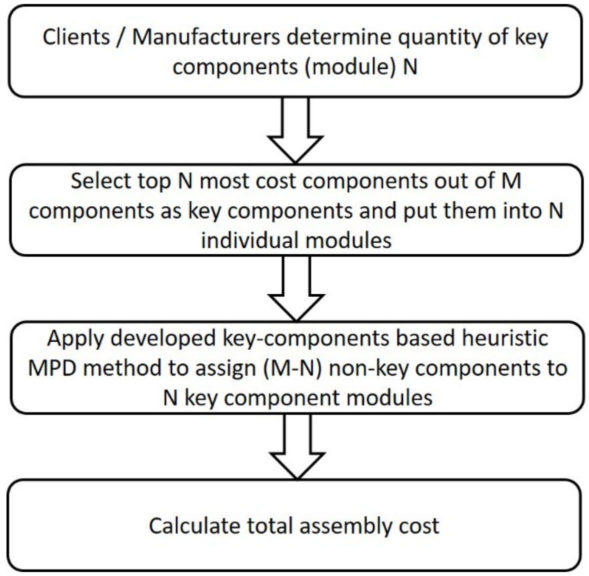


Figure 1 Steps of the Proposed MPD

The proposed methodology explores key components' impacts and improvement in the product assembly economics, and finally comes up with an MPD method to integrate these two factors. In this section, we discuss how to determine key components, components' connection relationships within a module, non-key component sorting and the heuristic for the MPD method.

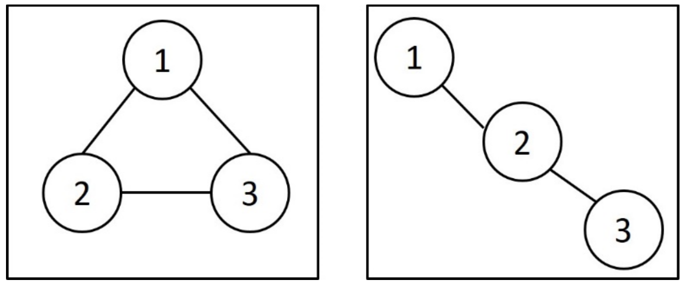
3.1 Key Components Determination and Handling

Key components may carry core technologies of the product, and they may represent costliest, most impactful to the environment, or most labor-time requiring parts in the product. In this paper, we consider the assembly cost, and therefore, we select the top market value components as key components. The quantity of key components is assumed to be given; this quantity can be determined by the manufacturer or the client according to company policy or expert (individual) perception.

Having multiple key components in the same module might cause problems (e.g., increasing the assembly difficulty and cost during maintenance). For example, the compressor and control unit in a refrigerator are expensive to manufacture and assemble. If two components are in the same module, during the maintenance when one is maintained, the other also needs to be disassembled and then assembled; this makes the maintenance more expensive and risky. Therefore, one good way to handle key components is to separate them into different modules. Consequently, key component quantity and module number should be equal.

3.2 Components within-Module Interaction

Components in the same module should connect to each other either directly or indirectly. Direct connection means two or more components have physical joints or they share common interfaces. For instance, in Fig. 2 part (a), component 1, 2, 3 are physically adjacent, and therefore they have direct connections. Indirect connection, on the contrary, means two components should join each other through one or more other components, but they do not have common interfaces. In Fig. 3 part (b), component 1 and 3 are both interacted with component 2, but they do not have common interactions; therefore, components 1 and 3 have an indirect connection.



(a) (b)

Figure 2 Component Connection Types with Module ((a): Direct Connection; (b): Indirect Connection)

3.3 Non-Key Component Sorting

Before applying key-component based MPD algorithm to conduct product assembly, key components and non-key components should be pre-determined. Non-key components should also be sorted according to ease of assembly principles (Stienstra, 2014); because different assembly sequences might cause various assembly complexities and ease of assembly principles could help identify the easiest sequence.

Ease of assembly depends on several factors; the most important one of which is the quantity of part-to-part interfaces. The more part-to-part interfaces two components have, the more difficult the assembly between them is. Therefore, when we determine non-key components' assembly sequence, we need to sort non-key components based on their quantity of interfaces. The component with the largest numbers of interfaces needs to be assigned into the pre-determined key component modules first. The more interfaces a component has, the higher priority it should be assigned. In addition to part-to-part interfaces, several other factors might also affect ease of assembly and thus need to be considered, such as component weight and component material. Consequently, to determine the order of non-key components, quantity of part-to-part interfaces should be considered first. If two non-key components share same number of part-to-part interfaces, the second determination criterion can be component weight, which requires the higher weight component to be allocated first. If two non-key components have the same weight, then we need to consider materials; metal alloy components are allocated priority over others in this case.

3.4 Key Component-based Heuristic MPD Algorithm

The proposed MPD algorithm is developed based on key component consideration within a product. Key components carry core technologies, or they might represent largest sustainability influencing parts. Fig. 3 illustrates the logic steps of the MPD algorithm.

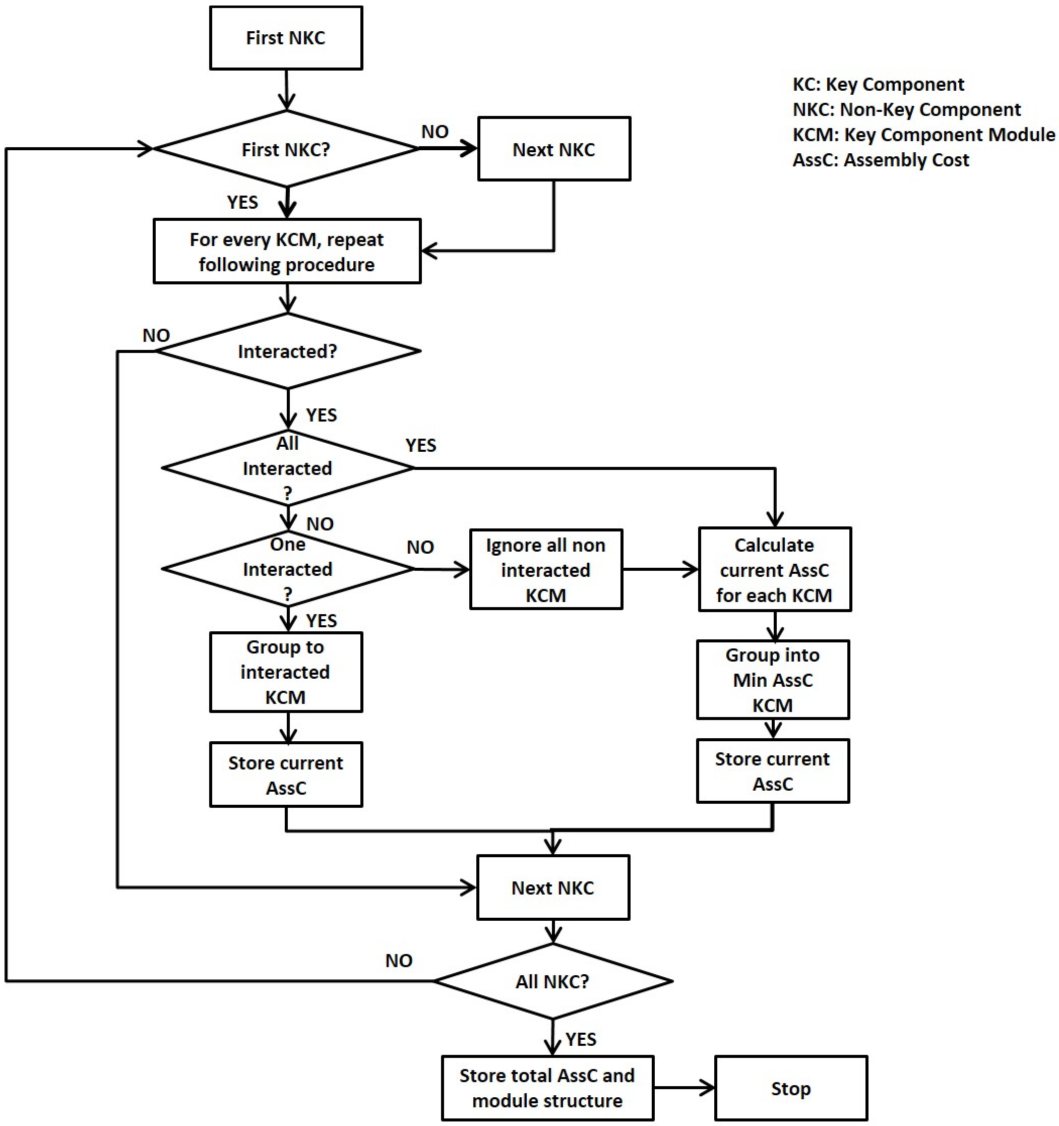


Figure 3 Key Component based MPD Algorithm Flow Chart

After the number of key components is determined externally, the top costliest components will be selected as key components and separated into different modules. These modules are key component modules, and all non-key components should be allocated into these modules. According to section 3.3, all non-key components are sorted. The first non-key component has the highest priority for assignment. This non-key component's physical connection relationships with other components already in each key component module will be checked. If no connections exist, this non-key component will be put into last order of the sorting, and the second sorted non-key component will replace it and enter into the algorithm. If there is a connection, the next step is to check whether this non-key component interacts with all key component modules. If all interactions are present, this non-key component will be assigned to the key component module with the lowest mutual assembly cost; if it only interacts with a few, all non-interacting key component modules will be ignored and this non-key component will be assigned to the interacting key component module with the lowest mutual assembly cost. An extreme case is that only one interaction occurs; then, this non-key component will go to this interacting key component module. After finishing such a search for one non-key component, the iteration will go to the next sorted non-key component until all non-key components are assigned. When the module structure is determined, the total assembly cost can be calculated.

4. Case Study

We use a coffee maker as a case study to show how to implement the proposed methodology. The case study is adopted from Chung et al. (2013), and the coffee maker product model is Mr. Coffee PR 15. The coffee maker components include only the main parts; small connectors, such as fasteners and screw bolts, are excluded from this case study. The data set for the coffee maker is primarily based on product dissection and supplemented by literature (Hula et al., 2003; Lee et al., 2001; Ulrich & Pearson, 1998) and online sites. Fig.4 shows the Mr. Coffee PR 15 coffee maker image, and Tab. 1 provides coffee maker attributes, including component names, component material, component market price, manufacturing price and manufacturing energy consumed. The physical connection relationships among components are presented in Fig.5's DSM matrix, where "0" means two corresponding components are not physically connected, and "1" means that they are connected. Fig.6 includes the corresponding assembly costs between components. For example, "0.01" at the intersection of row one and column two means that assembling component 1 and component 2 requires \$0.01. The assembly cost in this case study covers labor cost, material cost and energy consumption cost when completing the assembly procedure for two components.

Figure 4 Mr. Coffee PR 15 Coffee Maker

Table 1 The Components & Their Attributes in a Coffee Maker (Adopted from Chung, 2012)

No.	Component	Material	Weight (g)	Price (\$)	Mfg. Cost (\$)	Mfg. Energy (kWh)
1	Filter Basket	Plastic	90.8	3	0.94	0.290
2	Filter Basket Holder	Plastic	101.7	3	0.94	0.325
3	Lid	Plastic	52.7	2	0.64	0.168
4	Warming Plate	Steel	63.6	5	1.84	0.190
5	Main Housing	Plastic	1273.0	4	1.32	4.070
6	Heating Pipe	Steel	227.0	8	3.20	0.690

7	Carafe	Glass	348.7	10	3.30	0.058
8	Carafe Handle	Plastic/Steel	84.4	3	0.51	0.290
9	Bottom Plate	Steel	214.3	3	1.33	0.650
10	Power Cord	Copper/Plastic	60.8	2	0.80	0.003
11	Switch	Plastic/Metal	7.3	5	1.60	0.100

	1	2	3	4	5	6	7	8	9	10	11
1		1	0	0	0	0	0	0	0	0	0
2	1		0	0	1	0	0	0	0	0	0
3	0	0		0	1	0	0	0	0	0	0
4	0	0	0		1	1	1	0	0	0	0
5	0	1	1	1		1	0	0	1	1	1
6	0	0	0	1	1		0	0	0	0	1
7	0	0	0	1	0	0		1	0	0	0
8	0	0	0	0	0	0	1		0	0	0
9	0	0	0	0	1	0	0	0		0	0
10	0	0	0	0	1	0	0	0	0		1
11	0	0	0	0	1	1	0	0	0	1	

Figure 5 Connection Relations DSM (Adopted from Chung, 2012)

	1	2	3	4	5	6	7	8	9	10	11
1		0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.01		0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00		0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00		0.01	0.10	0.01	0.00	0.00	0.00	0.00
5	0.00	0.03	0.02	0.01		0.14	0.00	0.00	0.43	0.01	0.13
6	0.00	0.00	0.00	0.10	0.14		0.00	0.00	0.00	0.00	0.03
7	0.00	0.00	0.00	0.01	0.00	0.00		0.15	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.15		0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.43	0.00	0.00	0.00		0.00	0.00
10	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00		0.05
11	0.00	0.00	0.00	0.00	0.13	0.03	0.00	0.00	0.00	0.05	

Figure 6 Assembly Cost Design Structure Matrix (Adopted from Chung, 2012)

4.1 Key Components Determination and Handling

In our proposed methodology, clients and manufacturers will determine the key components number. In this coffee maker case study, we pre-determine four key components as the top four components with the highest market values: component 4 (Warming Plate), component 6 (Heating Pipe), component 7 (Carafe) and component 11 (Switch). These four key components will be assigned to four individual key component modules.

4.2 Key Component-Based Heuristic MPD Algorithm Results

The result of the key component-based algorithm depends on the order of non-key components' entry to the algorithm. Hence, we need to arrange the order of non-key components. We sort them according to the number of physical interfaces as shown in Fig. 5. For those non-key components that have the same number of interfaces, their component weight will be used to provide a unique order, given the consideration that the more weight the component has, the more difficult it is to assemble. Consequently, a specific priority of assembly will be given to the heavier component. After considering both the interface quantity and component weight, the sorted non-key components are listed in Tab. 2.

Table 2 Non-Key Component Order

Component Name	Main Housing (5)	Filter Basket Holder (2)	Power Cord (10)	Bottom Plate (9)	Filter Basket (1)	Carafe Handle (8)	Lid (3)
Interface #	7	2	2	1	1	1	1
Weight (g)	1273.0	101.7	60.8	214.3	90.8	84.4	52.7
Order	1	2	3	4	5	6	7

According to Tab. 2, the order of non-key components is: 5, 2, 10, 9, 1, 8 and 3. Applying the key-component based MPD algorithm to the coffee maker case study, and giving the order of non-key components, we could assign non-key components into the key component modules as in Tab. 3.

Table 3 Non-Key Components Module Assignment

Pre-Defined Module	Key Component 4 Module	Key Component 6 Module	Key Component 7 Module	Key Component 11 Module
Non-Key Components	1,2,3,4,5,9,10	6	7,8	11

According to Tab. 3, non-key component 1, 2, 3, 5, 9 and 10 are grouped into key component 4's module; non-key component 8 is grouped into key component 7's module; and key component 6 and 11's modules are single component modules. The assembly cost for this module structure is \$0.66, which was calculated using the information from Figure 6.

4.3 Sensitivity Analysis

In the proposed methodology, key component quantity is a variable to be determined by clients or manufacturers. We propose that the number of key components relies on the judgment of clients or manufacturers, and this decision represents the subjective perception and preference of decision-makers. Therefore, this quantity may impact the eventual modular design since various decision makers may have different preferences regarding core technology and sustainability consideration. In this case study, the sensitivity analysis emphasizes on identifying impact of the key component numbers on module structure determination and assembly cost calculation within the module. There are 11 components; thus, there could be 11 options for the key components quantity. For each of these key component numbers, module assignments and module assembly cost will be derived using the method described in section 3. The corresponding sensitivity analysis results are shown in Tab. 4. We note that the total module assembly costs are calculated as described when we introduced the proposed approach.

Table 4 Module Structure and Total Module Assembly Cost with Different Key Components

Pre-Defined Key Components #	Key Components	Module Assignments	Total Module Assembly Cost ($)
1	7	[1,2,3,4,5,6,7,8,9,10,11]	1.12
2	6,7	[1,2,3,5,6,9,10,11]; [4,7,8]	0.96
3	6,7,11	[1,2,3,5,9,10,11]; [6]; [4,7,8]	0.79
4	4,6,7,11	[1,2,3,4,5,9,10]; [6]; [7,8]; [11]	0.66
5	4,5,6,7,11	[1,2,3,5,9,10]; [4]; [6]; [7,8]; [11]	0.65
6	4,5,6,7,8,11	[1,2,3,5,9,10];[4];[6];[7];[8];[11]	0.50
7	1,4,5,6,7,8,11	[1,2];[3,5,9,10];[4];[6];[7];[8];[11]	0.47
8	1,2,4,5,6,7,8,11	[1];[2];[3,5,9,10];[4];[6];[7];[8];[11]	0.46
9	1,2,4,5,6,7,8,9,11	[1];[2];[3,5,10];[4];[6];[7];[8];[9];[11]	0.03
10	1,2,3,4,5,6,7,8,9,11	[1];[2];[3];[5,10];[4];[6];[7];[8];[9];[11]	0.01
11	1,2,3,4,5,6,7,8,9,10,11	[1]; [2]; [3]; [4]; [5]; [6]; [7]; [8];[9];[10];[11]	0.00

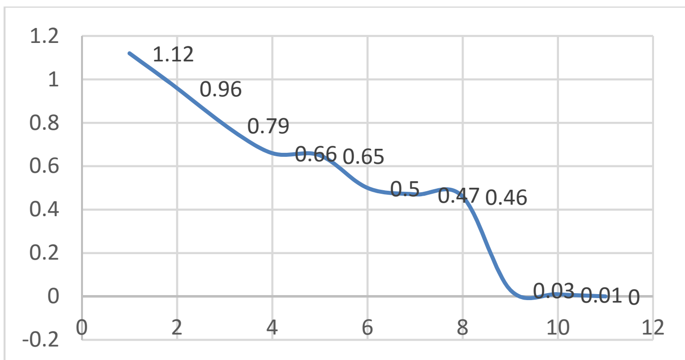


Figure 7 Key Component Quantity V.S. Module Assembly Cost

According to Tab. 4 & Fig. 7, each key component quantity has a unique module assignment as well as corresponding module assembly cost. With the increasing key component numbers, the module assembly cost will decrease, and module size/capacity will decrease accordingly. For example, one key component means all 11 components are in same module, and such module size/capacity is 11 components, and corresponding assembly cost is $1.12; while 11 key components mean each component is a single module, and each module size/capacity is one component, and corresponding assembly cost within module is 0.

4.4 Case Study Result Discussion

The case study pre-defines quantity of key components and therefore identifies the key components based on component market values. The reason is that these components account for a substantial part of the total product value, and the economic performance of the product greatly relies on these components. According to this criterion, the top four high-value components are selected: 4, 6, 7 and 11; and these four key components are assigned into four individual modules separating them. Non-key components are assigned to four key component modules based on the numbers of physical connections and component weights. Therefore, non-key components 1, 2, 3, 5, 9, 10 are grouped into key component 4's module; non-key component 8 is grouped into key component 7's module; and key component 6 and 11's modules are single component modules.

Huang and Kusiak (1998) developed the decomposition approach (DA), which discusses the interaction matrix and suitability matrix. The interaction matrix shows the pair-wise physical relationship among components and the suitability matrix shows designer's preferences. In the suitability matrix, there are four letters to represent four relationships between components in the same module: "a" for strongly desired, "e" for desired, "o" for strongly undesired and "u" for undesired. DA approach forms the module structure using the triangulation algorithm based on the interaction matrix and it partially handles key components in the suitability matrix by setting two key components as "strongly undesired", which will separate two key components into two individual modules. In order to compare results with the proposed methodology, we select components 4, 6, 7 and 11 as key components, and assign strongly undesired for any two of these key components in the suitability matrix. The corresponding interaction matrix and suitability matrix are shown in Fig. 8.

We have implemented the DA approach as we have done in our earlier work (Okudan et al., 2013; Ma & Kremer, 2013) and implementing the algorithm by Huang and Kusiak (1998) faithfully. The module structure of DA approach is [1, 2]; [3, 5, 9, 10, 11]; [7, 8]; [4]; [6]. It comes up with five modules even though we pre-determined four key components.

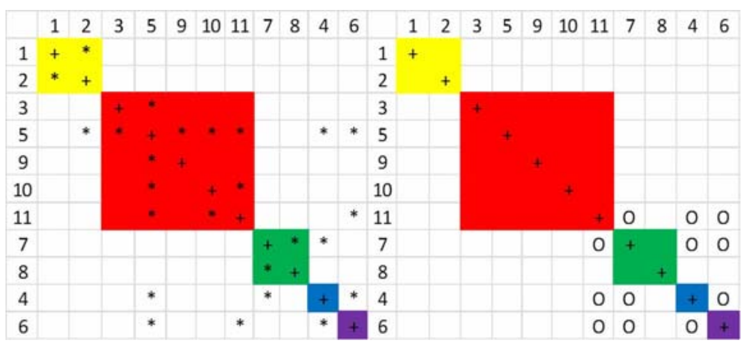


Figure 8 Decomposition Approach Result

The comparison between the results from DA and the proposed method is presented in Tab. 5. The DA approach yields the module assembly cost to be $0.75, which is higher than that from the proposed method. In addition, DA approach results in five modules, one more than that from the proposed method. A higher number of modules will usually cause a cost increase during the assembly procedure. Therefore, the proposed methodology has a significant potential advantage: lower assembly cost. However, experimentation with other products should be continued to further confirm this advantage.

Table 5 Coffee Maker Results Comparison

	New Methodology	Decomposition Approach
Key Component Identification	Assign key components into different modules	Set suitability matrix relationship between key components as "strongly undesired"
Clustering Algorithm Module Structure	Key-component based heuristic algorithm [1,2,3,4,5,9,10]; [6]; [7,8]; [11]	Triangurization algorithm [1,2];[3,5,9,10,11];[]7,8];[4];[6]

Module Assembly Cost	$0.66	12% reduction	$0.75	--

5. Applications in Interactive Engineering

Interactive engineering, as one of the informal names of "concurrent engineering", has received growing attention from both academia and industries due to its tremendous benefits to the economy. Interactive engineering is an engineering approach that decomposes the complex problem into several simple sub-problems that can be solved simultaneously. This approach can provide a holistic way to deal with complex systems. In addition to this primary meaning of interactive engineering, we believe that interactive engineering may also refer to customers' involvement in the design and manufacturing. The proposed approach could enhance the interactive engineering from the following perspectives: 1) Developing a modular based design method to tackle the assembly/disassembly sequence problem. The assembly/disassembly sequence problem is usually addressed as a systematic decomposition, and requires complicated mathematical computations. This approach decomposes the sequence problem into several sub-system problems with relatively simple calculations, and utilizes modularity to integrate components in the end. 2) Involving designers' opinion in the methodology development. Depending on the interactive communication between designers and customers, the quantity of key components were pre-determined, and then key components would be finalized by considering quantity and component individual values jointly. 3) Adoption in industry for assembly/disassembly operations. Since the algorithm requires only a few calculations, the implementation of this approach is simple and straightforward; and therefore, we expect that it will be easily adopted in the industrial settings.

6. Summary and Conclusion

In this paper, we propose a key component-based MPD methodology to reduce the assembly cost. The methodology considers the impact of key components on the product assembly, and provides a DFA approach in the form of an MPD algorithm. The methodology emphasizes on the analysis of key components, where key components are determined by a pre-defined key components quantity, component individual values (i.e., number of interfaces), and each key component occupies an individual module. The rest of the non-key components are assigned to key component modules according to physical interaction and mutual assembly cost with a specific sorted order. The module structure depends on the order of non-key component entries into the algorithm; hence, the order of non-key components is important. The order relies on component part-to-part interfaces quantity and component individual weight; and both of them are relevant to ease of assembly. The proposed methodology firstly considers key components in both MPD and product assembly, and the outcome shows that the assembly cost is reduced in comparison to a traditional MPD method, the Decomposition Approach (DA).

Even though the proposed methodology improves the product assembly economic performance, there are still limitations or space for potential improvements. The main constraint is the determination of the key component quantity is based on human input. The number of key components is a subjective input for this methodology, and it represents the individual perception or judgment from clients and manufacturers. The individual preference may not be always optimal or adequate in every situation. Moreover, the selection of key components depends on the component market value. In some cases, multiple components can share the same market value, which may make this methodology work in a more complicated way. Therefore, more detailed selection criteria need to be developed in order to fit different complicated conditions. In addition, this study addresses assembly cost within the module, and does not take into account the assembly cost among modules. Even though modularity can help to reduce the assembly cost, the reduced cost is not always from within module assembly.

In the future work, we will improve the methodology to eliminate the current limitations. We will develop a comprehensive approach for selecting key components. For example, theoretical minimum number of parts/components plays an essential role in determining assembly complexity in DFA (Storch, 2014), and conceptually, the theoretical minimum number of parts/components is similar to the quantity of key components. Therefore, we might use a similar method to determine key component quantity and then identify key components accordingly. Since the methodology can handle the economic performance improvement problem, it has potential to improve other sustainability performance in product design, such as environmental and social impacts. We could also modify the algorithm in order to fit the specific situation. For example, by using labor time as an indicator to measure social sustainability, we can switch “minimum cost” to “maximum labor time” in key component based MPD algorithm to develop a design for social sustainability MPD algorithm. The new algorithm will cluster higher labor time components into modules, and therefore increase total labor time used in the product. The more required labor hour will cause more job opportunities, and hence social sustainability performance can be improved. Additionally, a more holistic MPD algorithm with both within module assembly and among modules assembly consideration will be developed to simulate and represent the overall assembly procedure.

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