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利用原子理論於綠色產品設計

Green Product Design by Atomic Theory

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本論文係顏肇慶君（R96522630）在國立臺灣大學機械工程學系完成之碩士學位論文，於民國 98 年 7 月 3 日承下列考試委員審查通過及口試及格，特此證明

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摘要

伴隨著環境意識的抬頭與環保法規的設立,綠色產品設計在現今的產業中，不只佔有舉足輕重的角色，更是未來市場上的主要趨勢。在此篇論文中，作者提出一個創新的理論，利用原子理論的特性去解決產品設計中模組化設計的問題。藉由此創新的理論，可以將產品模組化加入一些綠色的限制條件，諸如材料的相容性、零件的可回收性以及零件的可拆卸性。除此之外，在產品設計上，利用原子理論將可幫助產品設計工程師於產品設計的初期，依據產品生命週期的需求，更有效率地創新產品綠色設計。當產品設計工程師在進行綠色產品設計時，必須將所需的綠色考量視為綠色設計限制條件。接著將對環境有相當影響性的綠色設計限制條件，加入原有產品的設計模組中，藉由此方法可以改良原有的模組，進而轉化成具有綠色設計考量的模組。在此篇論文中，作者也提出一個計算綠色貢獻度的評估方法，進而方便產品設計工程師去有效的評估每一個模組的綠色貢獻度。除此之外，產品設計工程師可以利用最後決定的模組去考量原有的設計是否需要重新設計。作者利用汽車雨刷馬達和檯燈為實例，實作如何利用原子理論有效率地進行綠色產品設計。

關鍵字：綠色產品設計、原子理論、模組化設計、產品生命週期、綠色產品評估。

Abstract

With increasing environmental consciousness and the establishment of environmental protection regulation, green product design not only plays a crucial role in modern industry but also is becoming the main focus of the future market. In this thesis, an innovative method is presented which uses the properties of atomic theory to solve design modularization problems for product design. With the developed method, products can be modularized based upon given green constraints, e.g., material compatibility, part recyclability, and part disassemblability. After green constraints are incorporated into new modules, a new design which improves upon the original design will be produced, with respect to environmental impacts. The developed method can help product design engineers effectively create green designs in the initial design stage, based on the product life-cycle requirements. In this thesis, a method for evaluating product green contributions is also developed to help product design engineers evaluate each module. In addition, the final modules can also help design engineers examine whether the original products need to be redesigned. A motor end of the windshield wiper and a table lamp are used as case study examples to show the effectiveness of the developed atomic theory-based green product design method.

Keywords: Green Product Design, Atomic Theory, Modular Design, Product Life-cycle, Green Product Evaluation

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Chapter 1. Introduction

1.1 Background

With increasing environmental consciousness and the establishment of environmental protection regulation, green product design not only plays a crucial role in modern industry but also is becoming the main focus on the future market. Customer needs are no longer satisfied only with the product functional and modeling design. Customers start to take into account whether a product complies with environmental regulations. Furthermore, in many countries, the promotion and implementation of environmental protection regulations make product green design an inevitable practice in industry. In this thesis, the research goal is to develop an efficient method to assist product design engineers to incorporate green design constraints into product life-cycle in the initial design stage to make their products more competitive in the global market.

1.2 Motivation and Purpose

Recently, research and methods related to green product design have advanced dramatically. However, currently, most green design analysis takes place at the remanufacturing stage. After a product is designed, manufacturing engineers conduct green analysis and then make necessary modifications to the existing design. However, conducting green analysis in the late stage of the design process often requires redesign of the whole product. Thus, using the traditional green design methods, green design can be difficult and ineffective due to conflicts with the original design constraints, e.g., structure, materials, and functions. Therefore, it is necessary for product design engineers to consider environmental impacts and green factors in the initial stage of the design life-cycle. Doing so can help guarantee that the products will be conformed to environmental regulations and also facilitate subsequent product maintenance, disassembly, and upgrade to improve product recycling, reuse, and remanufacturing. Thus, the purpose of this research is to develop a method which can help product design engineers incorporate environmental regulations into product designs in the early design stage.

1.3 Method

During the product green design process, product modularization often needs to be considered, to reduce product complexity and increase product disassembly efficiency. Modular design can promote product standardization, reduce transportation, simplify product upgrades, and save production time and cost. As a result, modular design plays an important role in green design and makes products more competitive.

In this thesis, an innovative method is presented which uses the properties of atomic theory to solve modularization problems in green product design. With the developed method, products can be modularized based upon given green design constraints, e.g., material compatibility, part recyclability, and part disassemblability. The developed method can help product design engineers effectively integrate green considerations into product designs in the initial design stage, based on the product life-cycle requirements.

After green constraints are incorporated into new modules, a new design which improves upon the original design will be produced, with respect to environmental impacts. The developed method can help product design engineers effectively create green designs in the initial design stage, based on the product life-cycle requirements. In this thesis, a method for evaluating product green contributions is also developed to help product design engineers evaluate each module. In addition, the final modules can also help design engineers examine whether the original products need to be redesigned.

1.4 Thesis Framework

In this thesis, we apply the properties of atoms to help product design engineers conduct modular designs, based upon green design requirements, in the initial stage of the product life-cycle design process. This thesis is organized as follows. Chapter 2 gives literature reviews concerning green product design. Chapter 3 introduces atomic theory and describes the method of applying atomic theory in modular design. Chapter 4 addresses the method of integrating green constraints in product design and introduces a green contribution value to evaluate modules. Chapter 5 presents two case studies, with implementation results. Two case studies are used to discuss the advantages and disadvantages of the developed methods. Finally, Chapter 6 offers conclusions.

Chapter 2. Literature Review

During green product design process, product modulization often needs to be considered, to reduce product complexity and increase disassembly efficiency. Modular design can promote product standardization ease of transportation, and save production time and cost [2-6, 8-9, 11-12, 15]. As a result, modular design plays an important role in green product design. Modular design can simplify product upgrades, as well as product recycling and maintenance, and thereby help reduce product life-cycle cost, which helps make products more competitive.

2.1 Modular Design

Kusiak and Huang [8, 9] used a functional concept to develop modular products by grouping or clustering sub-functions based upon functional relationships to form "functional" modules. Furthermore, they interpret three various types of modularity such as part-swapping, parts-sharing, and bus modularity, and use a graphical presentation to present product modularity. If product complexity is higher, it will become too difficult and complicated to use a functional concept to develop modular products. Modules generated based on a functional concept might not be available. It is because the modules are too early to be produced in the functional conceptual design stage, and it might conflict some structure constraints in the later design process. Therefore, in this research, we proposed that adding green design constraints after the structure modules are formed, and it is more practical to do modular design after the functional conceptual stage.

Gu and other researchers [3-5] formed modules based upon characteristic similarities between physical properties of parts, such as life span, material, maintenance level, disposal method, etc. Newcomb et al. [11] measured module correspondence, from several life-cycle viewpoints, and coupling between modules. Ulrich and Tung [15] have used a building bock system which been applied to develop the new machine tools by separating machine's main functionalities based on its architectures to form modules. Gershenson et al [2] proposed a modular design for mechanical pencil using the lifecycle concept.

The Design Structure Matrix (DSM) is a tool to perform both analysis and management of complex systems. A DSM is a square matrix and it lists all constituent subsystems and part relationship and dependency information. A directed graph is used to show the part dependencies for simple products. Some module operators are used to analyze and partition DSM for producing modules. Streward [12] used DSM to solve mathematical problems. After that, many researchers combine DSM with some artificial intelligent (AI) methods, such as cluster identification, fuzzy clustering analysis, or genetic algorithms, to do modular designs. Using DSM and AI can quickly get solutions but it might generate unreasonable or impractical solutions and it is hard to add additional design requirements. Here, we propose a green modular design method which can not only guarantee producing reasonable modules but can also add green design constraints to the products.

2.2 Modular Design by Using Artificial Intelligence

Among the modular design research, AI methods are extensively used because they can quickly find global-optimal or near-optimal solutions using random search techniques with high degrees of freedom. Stone, Wood, and Crawford [13] developed a heuristic algorithm which establishes a dominant flow among parts by analyzing branch flows for forming modules. However, their approach requires creating large databases. Gu, Hashemian and Sosale [4] used classical genetic algorithms to create modular designs.

Using their method, initial values for the number of modules and content size need to be set before the algorithms runs. Later, Gu and Sosale [5] used simulated annealing algorithms with an interaction matrix of parts to form modular designs. They only focused on physical relationships and design objective interactions among parts. Falkenauer [1] determined that classical genetic algorithms have three major limitations: encoding wastes space due to data redundancy, generating high quality offspring populations is not easy, and genetic operators tend to affect the quality of the offspring population. Falkenaur also used group genetic algorithms (GGAs) to deal with clustering problems and thereby to improve upon performance achieved with classical genetic algorithms.

Other researchers used group genetic algorithms (GGAs) in green product design. Falkenaur also used GGAs to deal with clustering problems and thereby to improve upon performance achieved with classical genetic algorithms. Kreng and Lee [7] used a case study to illustrate the capability of GGAs for modular design. They showed that, using their method, different population sizes and genetic operators could be modified to affect the results. Meehan, Duffy and Whitfield [10] used GGAs to explore the capabilities of modular design for promoting engineering "design for reuse" and developed a multi-view modular design methodology to fulfill design objectives. Tseng, Chang and Li [14] also used GGAs to form product modules. They used a cost index and a green pollution index to evaluate clustering results.

However, most methods which use GGAs have the same problems. First, they are easily trapped at local-optimal solutions. Second, when the complexity of a product increases, computational time increases dramatically. To overcome the limitations of prior methods, an innovative method was developed which uses atomic theory to solve the modular product design problem. An atom contains a positively charged atomic nucleus and negatively charged electrons. Because opposite electric charges attract each other and the same electric charges repel each other, each individual atom achieves a final structure.

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Chapter 3. Atomic Theory

3.1. Atomic Theory

Atomic theory was proposed by Dalton in 1803. Dalton established that "everything in nature is composed of atoms". In 1911, Rutherford found that an atomic nucleus carries a positive electrical charge. Rutherford then established the fundamental properties of the atomic theory, which include:

(1) An atom is composed of a positively charged atomic nucleus and negatively charged electrons.
(2) Like positive or negative electrical charges repel each other, while opposite electrical charges attract each other.
(3) A Coulomb force between charges causes them to either attract or repel each other.

3.2. Atomic Theory in Engineering Design

Generally, we all know that "everything in nature is composed of atoms". All kinds of products should be able to be solved and applied to some engineering problems such as grouping technology, imagine analysis and modularization problems by using the point of view of the fundamental properties of the atomic theory. Hence, an innovative method which uses the properties of atomic theory to solve a verity of engineering design problems is presented.

In atomic theory, the magnitude of the electrostatic force between two electric charges is calculated by Coulomb's law, as shown in Equation 1.

Coulomb's law:

$$F = k\frac{Q_1 Q_2}{{r_{12}}^2} \quad (1)$$

Q_1 : the electrical charge of the first object

Q_2 : the electrical charge of the second object

r_{12} : the separation distance between the two objects

k : Coulomb constant

The Coulomb force is proportional to the product of the magnitudes of the two charges and inversely proportional to the square of the distance between the charges. Using atomic theory in engineering design, we can calculate the Coulomb force of the positive and negative to observe the correlation between two objects. And the magnitudes of the Coulomb force is represented that the strength of the correlation between two objects.

As we using atomic theory to work in engineering design, the most important object is the positively charged atomic nucleus and the less important objects around the atomic nucleus are the negatively charged electrons. One atom contains positively and negatively charged objects, and if the valence number between them is equal, the atom is called electron neutral. In this thesis, atomic theory is applied to modular design for green product design.

3.3 Atomic Theory in Green Product Modular Design

In this thesis, we applied the properties of the atomic theory in product modular design. In our method, the modules in a product are modeled as atoms. The overall concept and approach of the developed method is to create modules by finding nucleus parts and calculate atomic forces that attract electrons to the nucleus parts, based on touching relationships and distances. Parts which touch more neighboring parts have higher complexities and are considered more important than parts with lower complexities. Therefore, in the developed approach, parts with more neighboring parts are modeled as positively charged atomic nuclei and their neighboring parts are modeled as negatively charged electrons. For example, in Figure 1, there are two modules. Part P_3 is an atomic nucleus, and parts P_1, P_2, P_4, and P_6 are electrons around the atomic nucleus P_3. As a result, part P_5 is repelled out of atom P_3 and becomes another atom by itself.

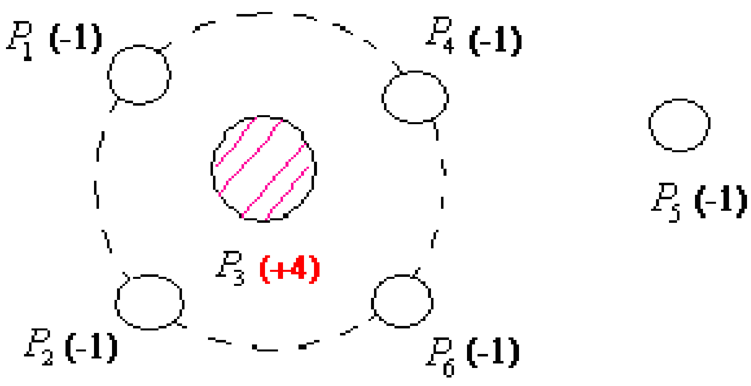

Figure 1. Atomic theory in modular design

In our method, we express Coulomb's law as Equation 2:

$$F_{ij} = -\frac{k_i k_j Q_i Q_j}{D_{ij}^{\ 2}} \tag{2}$$

Q_i : the electrical charge of part *i*

Q_j : the electrical charge of part *j*

D_{ij} : distance between parts *i* and *j*

k_i : a constant value for part *i*

k_j : a constant value for part *j*

To be consistent with a force matrix which is defined later, a negative sign is added so that if $Q_i \times Q_j > 0$, $F_{ij} < 0$; and if $Q_i \times Q_j < 0$, $F_{ij} > 0$.

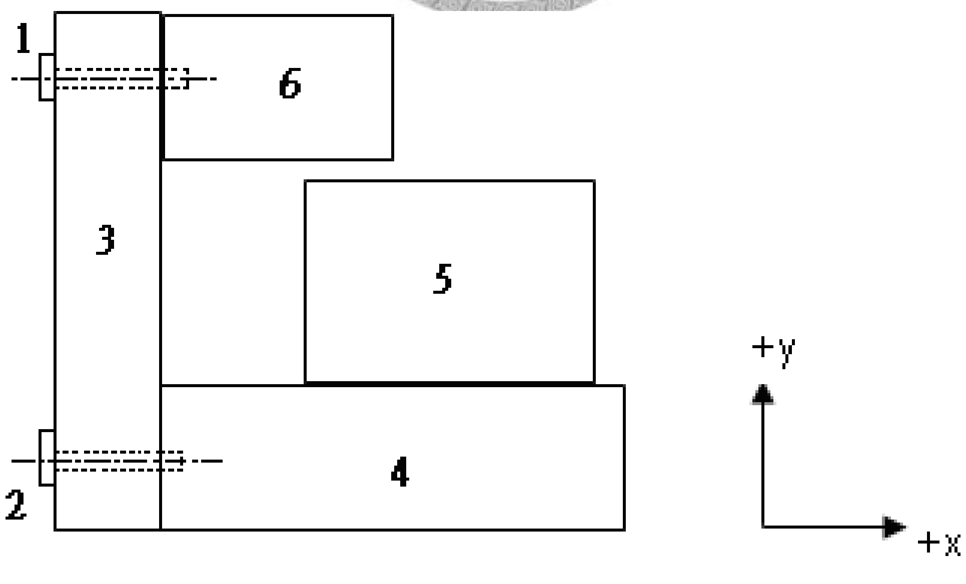

Figure 2. A simple example

3.3.1 Touch Matrix

Touch matrix T represents the touching relationship which includes any physical touch and connection relationship between each pair of parts.

$T_{ij} = 0$: part i and part j do not touch each other

$T_{ij} = 1$: part i and part j touch each other

$T_{ii} = 0$: the diagonal entries are zero

Thus, the touch matrix T for the product in Figure 1 is:

$$T = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 1 \\ 0 & 0 & 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 1 & 0 & 1 \\ 0 & 1 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 & 0 & 0 \end{bmatrix}$$

3.3.2 Total Touch Matrix and Valence Matrix

We define a *Total Touch matrix TT*, and $TT_i = \sum_{j=1}^{n} T_{ij}$, where n is the total number of parts in the product. We use *TT*, to show the number of touched parts associated with part i. Thus, the total touched matrix *TT* of the product in Figure 2 is:

$$TT = \begin{bmatrix} 2 \\ 2 \\ 4 \\ 3 \\ 1 \\ 2 \end{bmatrix}$$

Usually, if a part touches more parts, the part is relatively more important. Design engineers can choose threshold to determine the importance of a part. If, TT_i is greater than the threshold, that means part *i* is relatively more important. If TT_i is less than the threshold, that means part *i* is relatively less important. We define a *Valence matrix*, *Q*, to show the valences of the parts. If TT_i is greater than the threshold, $Q_i = TT_i$; otherwise, $Q_i = -1$. For example, in Figure 2, the threshold is 4, and, thus, part 3 is chosen as a positively charged atomic nucleus with a valence of +4. The other parts are then considered negatively charged electrons. Each electron is assigned a valence of -1. Thus, the Valence matrix *Q* for the product in Figure 2 is:

$$Q = \begin{bmatrix} -1 \\ -1 \\ +4 \\ -1 \\ -1 \\ -1 \end{bmatrix}$$

Product design engineers can establish the number of positively charged atomic nuclei (modules) desired based on requirements for the modules. In addition, when the product design engineers choice the positively charged nuclei, the total touch number must be greater than two. It is because if the total touch number is too small, the modules will be meaningless. If more modules are desired, more positively charged atomic nuclei can be chosen, and, as a result, more modules will be formed.

3.3.3 Distance Matrix

A *Distance matrix D* represents the distance between each pair of parts.

$D_{ij} = 1$: part *i* and part *j* touch each other

$D_{ij} = 2$: part *i* and part *j* do not touch each other

$D_{ii} = 0$: the diagonal entries are zero

Most parts are connected by fasteners, and fasteners greatly affect the efficiency of the recycling process. If we totally separate a fastener from the first touched part, the other connected part(s) will also be separated from the fastener. Thus, when creating the distance matrix, we only consider touching relationships between fasteners and their first touched parts. For example, in Figure 2, parts 1 and 2 are fasteners. Part 1 touches parts 3 and 6, and part 2 touches parts 3 and 4. Part 3 is the first touched part for parts 1 and 2. Therefore, we only consider the touching relationships between parts 1 and 3, and parts 2 and 3. Therefore, the *Distance* matrix *D* of the product in Figure 2 is:

$$D = \begin{bmatrix} 0 & 2 & 1 & 2 & 2 & 2 \\ 2 & 0 & 1 & 2 & 2 & 2 \\ 1 & 1 & 0 & 1 & 2 & 1 \\ 2 & 2 & 1 & 0 & 1 & 2 \\ 2 & 2 & 2 & 1 & 0 & 2 \\ 2 & 2 & 1 & 2 & 2 & 0 \end{bmatrix}$$

If the distance D_{ij} between two charges is larger, the force between them is correspondingly smaller.

3.3.4 Force Matrix

A *Force matrix, F*, is used to represent the attractive or repulsive forces between parts. For example, in Figure 2, only part 3 carries a positive charge of +4, while all other parts carry a negative charge of -1. Next, k values for parts with negative charges are set to 1. The force between parts 1 and 3 can then be calculated using Equation 2: $F_{13} = -\frac{k_1 k_3 Q_1 Q_3}{{D_{13}}^2} = -\frac{1 \times 1 \times (-1) \times (+4)}{1^2} = 4$. Thus, the corresponding *Force matrix*, *F*, for the product in Figure 2 is:

$$F = \begin{bmatrix} 0 & -0.25 & 4 & -0.25 & -0.25 & -0.25 \\ -0.25 & 0 & 4 & -0.25 & -0.25 & -0.25 \\ 4 & 4 & 0 & 4 & -0.25 & 4 \\ -0.25 & -0.25 & 4 & 0 & -1 & -0.25 \\ -0.25 & -0.25 & -0.25 & -1 & 0 & -0.25 \\ -0.25 & -0.25 & 4 & -0.25 & -0.25 & 0 \end{bmatrix}$$

The k value in Equation 2 is generally set to be *1*. If some positive charged atomic nuclei have the same valence number in the Valence matrix, Q, k values for the nuclei which have the same valence are sequentially increased by 1 to better differentiate between modules. For example, if for a given product, the parts associated with the five highest numbers in the *TT* matrix are chosen as positively charged atomic nuclei, and three of them have the same valence charges, k values associated with the three parts are set to 1, 2, and 3, respectively. With the given method, parts which are chosen as the positively charged atomic nuclei will not become negative charged electrons for other nuclei.

3.3.5 Maximum Force Matrix

The *Maximum Force matrix, MF,* is used to represent the maximum attractive force between one part and others, i.e., $MF_i = \max(F_{ij})$. For example, the *Maximum Force matrix, MF,* for the product in Figure 2 is:

$$MF = \begin{bmatrix} +4 \\ +4 \\ +4 \\ +4 \\ 0 \\ +4 \end{bmatrix}$$

After the *Maximum Force matrix* is obtained, the product modules can be formed by grouping parts with the same maximum attractive forces together. For example, the resulting modules for the product in Figure 2 are [1, 2, 3, 4, 6] and [5]. The total force on part 5 is a negative value, which means there is a net repulsive force between part 5 and other parts. Thus, part 5 is naturally repelled from the first module to become a separate module.

Chapter 4. Green Product Design

In the above sections, we can quickly get modules based on their physical touch relationship, so we can make sure the reasonable structure of the modules. However, product design engineers might need to consider adding other green design considerations into their product modular design, based on their requirements such as material compatibility, part recyclability, reusability, remanufacturing, etc. Here, we modify the *Distance matrix* to add the green design constraints to our original structure-based modules. By the same procedure we can obtain new modules which consider both the structure and green design constraint.

4.1. Green Modular Design

Conducting green product design is actually a process of adding "green" constraints to form green modules. Many constraints need to be considered in green product design, such as recycling, reuse, remanufacturing, controlling pollutants, etc. As an example, with our method, we can handle recycling constraints by defining a *Recycle Constraint matrix R,* where

$R_{ij} = 1$: if both parts *i* and *j* are recyclable or both not recyclable.

$R_{ij} = 0$: if one part is recyclable and the other is not recyclable.

$R_{ii} = 0$: the diagonal entries are zero

In Figure 2, if we assume parts 1, 2, 3, and 6 are recyclable, and parts 4 and 5 are not recyclable. The recycle constraint matrix *R* for the product in Figure 2 is given by:

$$R = \begin{bmatrix} 0 & 1 & 1 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 & 0 & 1 \\ 1 & 1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 1 & 1 & 1 & 0 & 0 & 0 \end{bmatrix}$$

We can then integrate the *Recycle Constraint matrix, R,* with the *Distance matrix, D,* to get an updated *Distance matrix*:

$$D_{ij} = D_{ij} \otimes R_{ij}\text{; where } \begin{cases} D_{ij} \times R_{ij} = 1, D_{ij} = 1 \\ D_{ij} \times R_{ij} \neq 1, D_{ij} = 2 \\ D_{ii} = 0 \end{cases}$$

After we integrate the recycle constraint into the *Distance matrix*, we get an updated *Distance matrix*:

$$\underset{\textit{Distance Matrix}}{\begin{bmatrix} 0 & 2 & 1 & 2 & 2 & 2 \\ 2 & 0 & 1 & 2 & 2 & 2 \\ 1 & 1 & 0 & 1 & 2 & 1 \\ 2 & 2 & 1 & 0 & 1 & 2 \\ 2 & 2 & 2 & 1 & 0 & 2 \\ 2 & 2 & 1 & 2 & 2 & 0 \end{bmatrix}} \otimes \underset{\textit{Recycle Constraint Matrix}}{\begin{bmatrix} 0 & 1 & 1 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 & 0 & 1 \\ 1 & 1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 1 & 1 & 1 & 0 & 0 & 0 \end{bmatrix}} = \underset{\textit{Distance Matrix}}{\begin{bmatrix} 0 & 2 & 1 & 2 & 2 & 2 \\ 2 & 0 & 1 & 2 & 2 & 2 \\ 1 & 1 & 0 & 2 & 2 & 1 \\ 2 & 2 & 2 & 0 & 1 & 2 \\ 2 & 2 & 2 & 1 & 0 & 2 \\ 2 & 2 & 1 & 2 & 2 & 0 \end{bmatrix}}$$

We can then replace the original *Distance matrix* and follow the same procedure to find the new *Force matrix* and *Maximum Force Matrix* for the given product to form green design modules. After considering the given green modular constraints, the new *Force matrix* for the product in Figure 2 is:

$$F = \begin{bmatrix} 0 & -0.25 & 4 & -0.25 & -0.25 & -0.25 \\ -0.25 & 0 & 4 & -0.25 & -0.25 & -0.25 \\ 4 & 4 & 0 & -0.25 & -0.25 & 4 \\ -0.25 & -0.25 & 1 & 0 & -1 & -0.25 \\ -0.25 & -0.25 & -0.25 & -1 & 0 & -0.25 \\ -0.25 & -0.25 & 4 & -0.25 & -0.25 & 0 \end{bmatrix}$$

The *Maximum Force matrix, MF,* is:

$$MF = \begin{bmatrix} +4 \\ +4 \\ +4 \\ +1 \\ 0 \\ +4 \end{bmatrix}$$

Therefore, the resulting new green design modules are [1, 2, 3, 6], [4], and [5]. The total forces on parts 4 and 5 are negative values, -0.75 and -2. It shows that there are repulsive forces between parts 4 and 5 and other parts. Thus, parts 4 and 5 are repelled out of other modules to form two separate modules. The results are compatible with our original constraint that parts 4 and 5 are not reusable, but parts 1, 2, 3 and 6 are reusable. The non-reusable parts are effectively isolated from the reusable parts into separate modules. The results show that our method can be used to effectively form new designed modules by adding green design constraints. Product design engineers can use our method to compare differences between their original designs and the new designed modules and then perform necessary design modifications.

4.2. Flowchart

Figure 3 describes our overall green product design by atomic theory. In the whole procedure, the product design engineers only need to create a touch matrix, and then the result modules will be quickly obtained by following the flowchart. If the product design engineers add other green design constraints, they can update the distance matrix and then get a green modules which are based on the original structure modules.

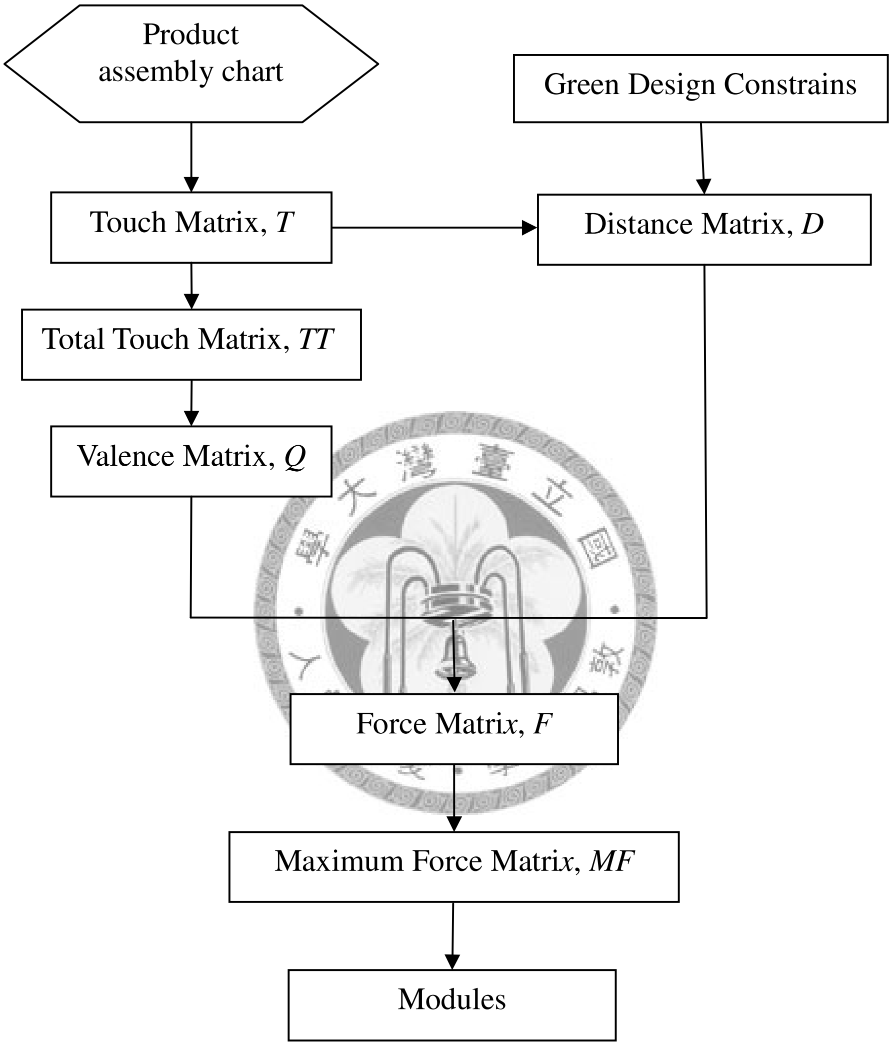

Figure 3. Atomic theory-based green product modular design flowing flowchart

4.3 Green Product Design and Evaluation

4.3.1 Green Product Design

With increasing environmental consciousness and the establishment of environmental protection regulation, product green design is an inevitable trend in the future. However, most green design analysis currently takes place at the remanufacturing stage. It is very inefficient and costly and, in the worse case, the whole product might need to be redesigned. Therefore, in this thesis, we proposed an innovative method using atomic theory to help designers conduct green product modular design in the early design stage.

During the green design process, designers can add green design constraints, such as material compatibility, part recyclability, reusability, remanufacturing, etc, into their designs, based on the design requirements. After that, we can get new modules which contain green design considerations. In the next section, we propose a new evaluation method, called "*Green Contribution*", to calculate the green value for each type of modules. An example is given to demonstrate how the green product modules is selected and evaluated.

4.3.2 Product Modules Selection and Evaluation

After we add the green design constraints, we will form some modules. In this section, we propose using "*Green Contribution"* to be our evaluation index and represent the green contribution of a product. Using atomic theory, we will firstly produce a set of modules based only on the touch relationships, and they are named as "structure modules" here. In order to help design engineers form green modules, a green contribution value is used to evaluate each set of modules.

The *Green Contribution* contains *Modular Index, Recycle Index* and *Reuse Index*. Designers can add more indices in the green contribution value.

$$Green\ Contribution = Modular\ Index + Recycle\ Index + Reuse\ Index \tag{3}$$

Modular Index represents the degree of modulization of a product. It can be obtained by equation 4.

Modular Index:

$$Modular\ Index = 1 - \frac{Number\ of\ Modules}{Number\ of\ Components} \tag{4}$$

The modular index is between 0 and 1. A product with a higher modular index will have a greater degree of modularization. A product having a higher modular index will have more advantages, such as less handling cost, less manufacturing cost, higher disassemblability, etc.

Recycle Index is an assessment index to represent the recyclability of a product. It can be obtained by equation 5.

Recycle Index:

$$Recycle\ Index = \sum_{i=1}^{n} \left(\frac{NetWeight_{Part}}{NetWeight_{Modulei}} \right) \tag{5}$$

$NetWeight_{Part}$: the net weight of the recyclable parts in the *ith* module

$NetWeight_{Modulei}$: the net weight of the whole module of the *ith* module

Product design engineers can use the recycle index to check whether a product conforms to the environmental protection regulations in the initial stage of product life-cycle design. Product design engineers usually use CAD systems to build a product assembly chart or design chart, and it can automatically calculate the net weight of each part. Hence, design engineers can quickly calculate the recycle index in the initial stage of product life-cycle design.

Reuse Index is an assessment to represent the reusability of a product. It can be obtained by equation 6.

Reuse Index:

$$Reuse\ Index = \sum_{i=1}^{n}\left(\frac{NetWeight_{Part}}{NetWeight_{Modulei}}\right) \tag{6}$$

$NetWeight_{Part}$ **:** the net weight of the reusable parts in the *ith* module

$NetWeight_{Modulei}$: the net weight of the whole module of the *ith* module

Product design engineers can use the reuse index to check whether a product conforms to the environmental protection regulations in the initial stage of product life-cycle design. Product design engineers can quickly calculate the reuse index in the initial stage of product life-cycle design.

We used an example to show the details of how to evaluate modules using the defined indices. Assuming there is a product of 10 parts. At first, we have known parts 4 and 8 cannot be recycled, and part 7 can be both reused and recycled, other components can only be recycled. The Wikipedia defines reuse and recycle as: “Reuse is to use an item more than once. This includes conventional reuse where the item is used again for the same function, and new-life reuse where it is used for a new function. In contrast, recycling is the breaking down of the used item into raw materials which are used to make new items." We used the developed atomic theory to conduct product modular design, and we can get the structure modules. After that, we add the recycle and reuse constraints to form recycle modules and reuse modules. We also define "Intersection Modules", as shown in Equation 7, which are the intersection of the structure modules and all other green modules, e.g., recycle modules and reuse modules. Table 1 shows the different kinds of modules.

$$Intersection\,Modules = Structure\,Modules \cap Recycle\,Modules \cap Reuse\,Modules \tag{7}$$

Table 1. All type of modules.

Structure Modules	[1,2,3,4], [5,6,7], [8], [9,10]
Recycle Modules	[1,2,3], [5,6,7], [4], [8], [9,10]
Reuse Modules	[1,2,3,4], [5,6], [7], [8], [9,10]
Intersection Modules	[1,2,3], [5,6], [8], [9,10], [4], [7]

We now can calculate the design indices for each set of modules. For convenience, we assume that the net weight of each part is 1 kg.

(1) Structure Modules: [1,2,3,4], [5,6,7], [8], [9,10]

Modular Index $= 1 - \frac{4}{10} = 0.6$

Recycle Index $= (\frac{3}{4} + 1 + 0 + 1) = 2.75$

Reuse Index $= (0 + \frac{1}{3} + 0 + 0) = 0.33$

Green Contribution = 0.6+2.75+0.33 = 3.68

(2) Recycle Modules:[1,2,3], [5,6,7], [4], [8], [9,10]

Modular Index $= 1 - \frac{5}{10} = 0.5$

Recycle Index $= (1 + 1 + 0 + 0 + 1) = 3$

Reuse Index $= (0 + \frac{1}{3} + 0 + 0 + 0) = 0.33$

Green Contribution = 0.5+3+0.33 =3.83

(3) Reuse Modules: [1,2,3,4], [5,6], [7], [8], [9,10]

Modular Index $= 1 - \frac{5}{10} = 0.5$

Recycle Index $= (\frac{3}{4} + 1 + 1 + 0 + 1) = 3.75$

Reuse Index $= (0 + 0 + 1 + 0 + 0) = 1$

Green Contribution = 0.5+3.75+1 = 5.25

(4) Intersection Modules: [1,2,3], [5,6], [8], [9,10], [4], [7]

Modular Index $= 1 - \frac{6}{10} = 0.4$

Recycle Index $= (1 + 1 + 0 + 1 + 0 + 1) = 4$

Reuse Index $= (0 + 0 + 0 + 0 + 0 + 1) = 1$

Green Contribution = 0.4+4+1 = 5.4

Product design engineers can choose modules for product redesign based on the green contribution value. Here, since the intersection modules have the highest green contribution, we choose it for our product redesign.

Before redesign, the *Original Green Contribution* (OGC) value is equal to the green contribution value of the structure modules, and it is 3.68. After redesign, the *New Green Contribution* (NGC) value is 5.4 for the intersection modules. *Green Updating Rate*, as shown in Equation 8, can help product design engineers to examine the differences between the original design and the new design.

$$Green\ Updating\ Rate = \frac{NGC - OGC}{OGC} \times 100\% \qquad (8)$$

In the example product, OGC is 3.68 and NGC is 5.4, so the green updating rate is $\frac{5.4-3.68}{3.68} \times 100\% = 46.7\%$. Since the intersection modules contain the attributes of recycle and reuse, after redesign, the recycle and reuse considerations are both in the new product. Thus, product design engineers can use the developed atomic theory to conduct green modules selections and evaluations.

Chapter 5. Case Study

5.1 A motor end of the windshield wiper

In the following case study, we apply the developed method to a motor system locating at the end of the windshield wiper [16]. There are twenty parts in the motor, as shown in Figure 4.

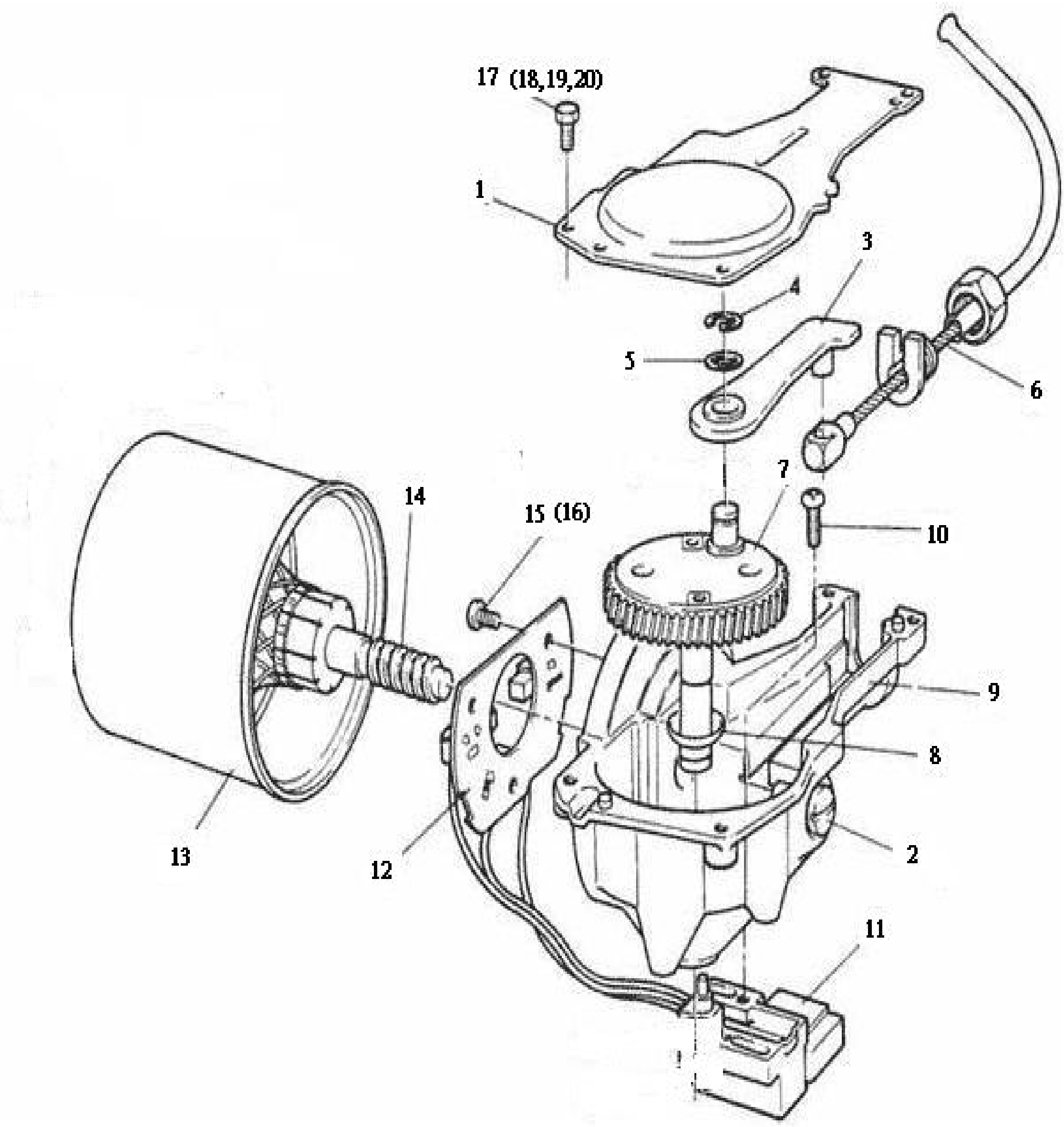

Figure 4. A motor end of the windshield wiper

5.1.1 Touch Matrix

With our method, product design engineers can decide the approximate number of positively charged atomic nuclei (modules) they would like in their final design, based upon product and module requirements. If they choose more positively charged atomic nuclei, more modules are formed. For the given case study, we decided that any parts with more than three touching relationships would be chosen to be positively charged atomic nuclei.

5.1.2 Total Touch Matrix and Valence Matrix

The resulting Touch matrix T is shown in Table 2. Total Touch matrix TT and Valence matrix Q are shown as follows. Here, we set the threshold value as three. Thus, there are four positively charged atomic nuclei which touch more than three parts, which are parts 1, 7, 9 and 12. The rest of the parts were assigned to be negatively charged electrons.

Table 2. Touch matrix, for product in Figure 4

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1
2	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0
3	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
4	1	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	1	1	1	0	0	1	0	0	1	0	0	1	0	0	0	0	0	0
8	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0
9	0	1	0	0	0	0	0	1	0	1	1	1	0	0	1	1	1	1	1	1
10	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	1	0	1	0	0	0	1	1	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
14	0	1	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0
17	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
18	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
19	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
20	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0

$$TT = \begin{bmatrix} 5 \\ 2 \\ 3 \\ 3 \\ 3 \\ 1 \\ 6 \\ 2 \\ 11 \\ 1 \\ 3 \\ 4 \\ 1 \\ 3 \\ 2 \\ 2 \\ 2 \\ 2 \\ 2 \\ 2 \end{bmatrix} \qquad Q = \begin{bmatrix} +5 \\ -1 \\ -1 \\ -1 \\ -1 \\ -1 \\ +6 \\ -1 \\ +11 \\ -1 \\ -1 \\ +4 \\ -1 \\ -1 \\ -1 \\ -1 \\ -1 \\ -1 \\ -1 \\ -1 \end{bmatrix}$$

5.1.3 Distance Matrix

Most parts are connected by fasteners, and fasteners greatly affect the efficiency of the recycling process. If we totally separate a fastener from the first touched part, the other connected part(s) will also be separated from the fastener. Thus, when creating the distance matrix, we only consider touching relationships between fasteners and their first touched parts. For example, in Figure 4, parts 10, part 15, part 16, part 17, part 18, part 19 and part 20 are fasteners. Therefore, the *Distance* matrix D of the product in Figure 4 is shown in Table 3.

5.1.4 Force Matrix

From the *Valence matrix Q*, we know that parts 1, 7, 9 and 12 are positively charged atomic nuclei and the rest of the parts are negatively charged electrons. The k value in Equation 2 is generally set to be one. However, when some positively charged atomic nuclei have the same valence value, in *Valence matrix Q*, the value of k is increased sequentially for the given parts.

Table 3. Distance matrix for product in Figure 4

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	0	2	2	1	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1	1
2	2	0	2	2	2	2	2	2	1	2	2	2	2	1	2	2	2	2	2	2
3	2	2	0	2	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2
4	1	2	2	0	1	2	1	2	2	2	2	2	2	2	2	2	2	2	2	2
5	2	2	1	1	0	2	1	2	2	2	2	2	2	2	2	2	2	2	2	2
6	2	2	1	2	2	0	2	2	2	2	2	2	2	2	2	2	2	2	2	2
7	2	2	1	1	1	2	0	1	2	2	1	2	2	1	2	2	2	2	2	2
8	2	2	2	2	2	2	1	0	1	2	2	2	2	2	2	2	2	2	2	2
9	2	1	2	2	2	2	2	1	0	1	1	1	2	2	1	1	1	1	1	1
10	2	2	2	2	2	2	2	2	1	0	2	2	2	2	2	2	2	2	2	2
11	2	2	2	2	2	2	1	2	1	2	0	1	2	2	2	2	2	2	2	2
12	2	2	2	2	2	2	2	2	1	2	1	0	2	2	1	1	2	2	2	2
13	2	2	2	2	2	2	2	2	2	2	2	2	0	1	2	2	2	2	2	2
14	2	1	2	2	2	2	1	2	2	2	2	2	1	0	2	2	2	2	2	2
15	2	2	2	2	2	2	2	2	1	2	2	1	2	2	0	2	2	2	2	2
16	2	2	2	2	2	2	2	2	1	2	2	1	2	2	2	0	2	2	2	2
17	1	2	2	2	2	2	2	2	1	2	2	2	2	2	2	2	0	2	2	2
18	1	2	2	2	2	2	2	2	1	2	2	2	2	2	2	2	2	0	2	2
19	1	2	2	2	2	2	2	2	1	2	2	2	2	2	2	2	2	2	0	2
20	1	2	2	2	2	2	2	2	1	2	2	2	2	2	2	2	2	2	2	0

Table 4. Force matrix for product in Figure 4

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	0	1.25	1.25	5	1.25	1.25	-7.5	1.25	-13.75	1.25	1.25	-5	1.25	1.25	1.25	1.25	5	5	5	5
2	1.25	0	-0.25	-0.25	-0.25	-0.25	1.5	-0.25	11	-0.25	-0.25	1	-0.25	-1	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25
3	1.25	-0.25	0	-0.25	-1	-1	6	-0.25	2.75	-0.25	-0.25	1	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25
4	5	-0.25	-0.25	0	-1	-0.25	6	-0.25	2.75	-0.25	-0.25	1	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25
5	1.25	-0.25	-1	-1	0	-0.25	6	-0.25	2.75	-0.25	-0.25	1	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25
6	1.25	-0.25	-1	-0.25	-0.25	0	1.5	-0.25	2.75	-0.25	-0.25	1	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25
7	-7.5	1.5	6	6	6	1.5	0	6	-16.5	1.5	6	-6	1.5	6	1.5	1.5	1.5	1.5	1.5	1.5
8	1.25	-0.25	-0.25	-0.25	-0.25	-0.25	6	0	11	-0.25	-0.25	1	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25
9	-13.75	11	2.75	2.75	2.75	2.75	-16.5	11	0	11	11	-44	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75
10	1.25	-0.25	-0.25	-0.25	-0.25	-0.25	1.5	-0.25	11	0	-0.25	1	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25
11	1.25	-0.25	-0.25	-0.25	-0.25	-0.25	6	-0.25	11	-0.25	0	4	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25
12	-5	1	1	1	1	1	-6	1	-44	1	4	0	1	1	4	4	1	1	1	1
13	1.25	-0.25	-0.25	-0.25	-0.25	-0.25	1.5	-0.25	2.75	-0.25	-0.25	1	0	-1	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25
14	1.25	-1	-0.25	-0.25	-0.25	-0.25	6	-0.25	2.75	-0.25	-0.25	1	-1	0	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25
15	1.25	-0.25	-0.25	-0.25	-0.25	-0.25	1.5	-0.25	2.75	-0.25	-0.25	4	-0.25	-0.25	0	-0.25	-0.25	-0.25	-0.25	-0.25
16	1.25	-0.25	-0.25	-0.25	-0.25	-0.25	1.5	-0.25	2.75	-0.25	-0.25	4	-0.25	-0.25	-0.25	0	-0.25	-0.25	-0.25	-0.25
17	5	-0.25	-0.25	-0.25	-0.25	-0.25	1.5	-0.25	2.75	-0.25	-0.25	1	-0.25	-0.25	-0.25	-0.25	0	-0.25	-0.25	-0.25
18	5	-0.25	-0.25	-0.25	-0.25	-0.25	1.5	-0.25	2.75	-0.25	-0.25	1	-0.25	-0.25	-0.25	-0.25	-0.25	0	-0.25	-0.25
19	5	-0.25	-0.25	-0.25	-0.25	-0.25	1.5	-0.25	2.75	-0.25	-0.25	1	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25	0	-0.25
20	5	-0.25	-0.25	-0.25	-0.25	-0.25	1.5	-0.25	2.75	-0.25	-0.25	1	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25	0

The *Force matrix F* can be easily calculated. For example, the force between parts 7 and 9 is $F_{79} = -\frac{k_7 k_9 Q_7 Q_9}{D_{79}{}^2} = -\frac{1\times1\times(+6)\times(+11)}{2^2} = -16.5$. Finally, the *Force matrix* of this case study is shown in Table 4.

5.1.5 Maximum Force Matrix

From the *Force matrix*, the *Maximum Force matrix*, *MF*, can be obtained:

$$MF = \begin{bmatrix} +5 \\ +11 \\ +6 \\ +6 \\ +6 \\ +1 \\ +6 \\ +11 \\ +11 \\ +11 \\ +11 \\ +4 \\ +1 \\ +6 \\ +4 \\ +4 \\ +5 \\ +5 \\ +5 \\ +5 \end{bmatrix}$$

From the *Maximum Force matrix*, we know that [MF_{12}, MF_{15}, MF_{16}] = +4, [MF_1, MF_{17}, MF_{18}, MF_{19}, MF_{20}] = +5, [MF_2, MF_8, MF_9, MF_{10}, MF_{11}] = +11, [MF_3, MF_4, MF_5, MF_7, MF_{14}] = +6, [MF_6] = +1, and [MF_{13}] = +1. Since parts which have more than three touched parts are assigned positive valences, the minimum force should be:

$$F_{\min} = -\frac{k_i k_{\min} Q_i Q_{\min}}{D_{\min}^{\ 2}} = -\frac{1\times 1\times(-1)\times(+4)}{1^2} = 4$$

Here, the force values for MF_6 and MF_{13} are less than 4. Therefore, MF_6 and MF_{13} can be regarded as two individual modules. Thus, the resulting modules are [1,17,18,19,20], [2,8,9,10,11], [3,4,5,7,14], [12,15,16], [6],[13], as shown in Figure 5.

5.1.6 Green Product Design

In the above sections, we have obtained modules based on their physical touch relationships, so the structure of the modules should be reasonable. Furthermore, if product design engineers need to consider adding other green design considerations to their product, by using the method in Chapter 4, they can add any green design constraints based on their requirements.

In this case study, in Figure 4, we assumed part 14 can be reused. Parts 3 and 11 can not be recycled but others can be recycled. We added the green design constraints to our original structure-based modules. The updated *Distance matrixes* of the recyclable constraints and the reusable constraints are shown in Table 5 and Table 6.

Table 5. The Distance matrix of the recyclable constraints for product in Figure 4

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	0	2	2	1	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1	1
2	2	0	2	2	2	2	2	2	1	2	2	2	2	1	2	2	2	2	2	2
3	2	2	0	2	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2
4	1	2	2	0	1	2	1	2	2	2	2	2	2	2	2	2	2	2	2	2
5	2	2	1	1	0	2	1	2	2	2	2	2	2	2	2	2	2	2	2	2
6	2	2	1	2	2	0	2	2	2	2	2	2	2	2	2	2	2	2	2	2
7	2	2	2	1	1	2	0	1	2	2	1	2	2	1	2	2	2	2	2	2
8	2	2	2	2	2	2	1	0	1	2	2	2	2	2	2	2	2	2	2	2
9	2	1	2	2	2	2	2	1	0	1	2	1	2	2	1	1	1	1	1	1
10	2	2	2	2	2	2	2	2	1	0	2	2	2	2	2	2	2	2	2	2
11	2	2	2	2	2	2	1	2	2	2	0	1	2	2	2	2	2	2	2	2
12	2	2	2	2	2	2	2	2	1	2	1	0	2	2	1	1	2	2	2	2
13	2	2	2	2	2	2	2	2	2	2	2	2	0	1	2	2	2	2	2	2
14	2	1	2	2	2	2	1	2	2	2	2	2	1	0	2	2	2	2	2	2
15	2	2	2	2	2	2	2	2	1	2	2	1	2	2	0	2	2	2	2	2
16	2	2	2	2	2	2	2	2	1	2	2	1	2	2	2	0	2	2	2	2
17	1	2	2	2	2	2	2	2	1	2	2	2	2	2	2	2	0	2	2	2
18	1	2	2	2	2	2	2	2	1	2	2	2	2	2	2	2	2	0	2	2
19	1	2	2	2	2	2	2	2	1	2	2	2	2	2	2	2	2	2	0	2
20	1	2	2	2	2	2	2	2	1	2	2	2	2	2	2	2	2	2	2	0

Table 6. The Distance matrix of the reusable constraints for product in Figure 4

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	0	2	2	1	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1	1
2	2	0	2	2	2	2	2	2	1	2	2	2	2	1	2	2	2	2	2	2
3	2	2	0	2	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2
4	1	2	2	0	1	2	1	2	2	2	2	2	2	2	2	2	2	2	2	2
5	2	2	1	1	0	2	1	2	2	2	2	2	2	2	2	2	2	2	2	2
6	2	2	1	2	2	0	2	2	2	2	2	2	2	2	2	2	2	2	2	2
7	2	2	1	1	1	2	0	1	2	2	1	2	2	2	2	2	2	2	2	2
8	2	2	2	2	2	2	1	0	1	2	2	2	2	2	2	2	2	2	2	2
9	2	1	2	2	2	2	2	1	0	1	1	1	2	2	1	1	1	1	1	1
10	2	2	2	2	2	2	2	2	1	0	2	2	2	2	2	2	2	2	2	2
11	2	2	2	2	2	2	1	2	1	2	0	1	2	2	2	2	2	2	2	2
12	2	2	2	2	2	2	2	2	1	2	1	0	2	2	1	1	2	2	2	2
13	2	2	2	2	2	2	2	2	2	2	2	2	0	1	2	2	2	2	2	2
14	2	1	2	2	2	2	2	2	2	2	2	2	1	0	2	2	2	2	2	2
15	2	2	2	2	2	2	2	2	1	2	2	1	2	2	0	2	2	2	2	2
16	2	2	2	2	2	2	2	2	1	2	2	1	2	2	2	0	2	2	2	2
17	1	2	2	2	2	2	2	2	1	2	2	2	2	2	2	2	0	2	2	2
18	1	2	2	2	2	2	2	2	1	2	2	2	2	2	2	2	2	0	2	2
19	1	2	2	2	2	2	2	2	1	2	2	2	2	2	2	2	2	2	0	2
20	1	2	2	2	2	2	2	2	1	2	2	2	2	2	2	2	2	2	2	0

We used the atomic theory to perform product modular design and get the structure modules. After we added the recycle (or reuse) green design constraints, we can get the recycle (or reuse) modules. Finally, we can obtain the intersection modules. All types of modules in this case study are shown in Table 7.

Table 7. All type of modules for product in Figure 4

Structure Modules	[1,17,18,19,20], [2,8,9,10,11], [3,4,5,7,14], [12,15,16], [6],[13]
Recycle Modules	[1,17,18,19,20],[2,8,9,10],[4,5,7,14],[12,15,16],[6],[13],[3],[11]
Reuse Modules	[1,17,18,19,20],[2,8,9,10,11],[3,4,5,7], [12,15,16], [6],[13],[14]
Intersection Modules	[1,17,18,19,20],[2,8,9,10],[4,5,7],[12,15,16],[6],[13],[14],[3],[11]

We used the green contribution value to evaluate each module. The *Green Contribution* contains *Modular Index, Recycle Index* and *Reuse Index*. If we need to add other green design constraints, we can add other indices in the green contribution value. From Table 7, we can calculate each type of modules. For convenience, we assume that the net weight of each part is 1 kg.

(1) Structure Modules: [1,17,18,19,20], [2,8,9,10,11], [3,4,5,7,14], [12,15,16], [6], [13]

Modular Index $= 1 - \frac{6}{20} = 0.7$

Recycle Index $= (1 + \frac{4}{5} + \frac{4}{5} + 1 + 1 + 1) = 5.6$

Reuse Index $= (0 + 0 + \frac{1}{5} + 0 + 0 + 0) = 0.2$

Green Contribution = 0.7+5.6+0.2 = 6.5

(2) Recycle Modules: [1,17,18,19,20], [2,8,9,10], [4,5,7,14], [12,15,16], [6], [13], [3], [11]

Modular Index $= 1 - \frac{8}{20} = 0.6$

Recycle Index $= (1 + 1 + 1 + 1 + 1 + 1 + 0 + 0) = 6$

Reuse Index $= (0 + 0 + \frac{1}{4} + 0 + 0 + 0 + 0 + 0) = 0.25$

Green Contribution = 0.6+6+0.25 = 6.85

(3) Reuse Modules: [1,17,18,19,20], [2,8,9,10,11], [3,4,5,7], [12,15,16], [6], [13], [14]

Modular Index $= 1 - \frac{7}{20} = 0.65$

Recycle Index $= (1 + \frac{4}{5} + \frac{3}{4} + 1 + 1 + 1 + 1) = 5.31$

Reuse Index $= (0 + 0 + 0 + 0 + 0 + 0 + 1) = 1$

Green Contribution = 0.65+5.31+1 = 6.96

(4) Intersection Modules: [1,17,18,19,20], [2,8,9,10], [4,5,7,14], [12,15,16], [6], [13], [14], [3], [11]

Modular Index $= 1 - \frac{9}{20} = 0.55$

Recycle Index $= (1 + 1 + 1 + 1 + 1 + 0 + 1 + 0 + 1) = 7$

Reuse Index $= (0 + 0 + 0 + 0 + 0 + 0 + 1 + 0 + 0) = 1$

Green Contribution = 0.55+7+1 = 8.55

Product design engineers can choose modules based on the green contribution value. The intersection modules can be selected to be our final modules for green product design from the green contribution values.

5.1.7 Merging

If a module has only one connection relationship with another module, the disassembly time and disassembly difficulty is minimized, which is considered to be the best case for modular design. Therefore, an atom meets the best condition if the total sum of the positive charges and negative charges in the atom is one. We define this condition as "full loading". A total which is not one implies that the module has more than one touching relationship with other adjacent modules, and the module is in a “non-full loading” condition. For example, part 1 is in full loading, and parts 6, 7, 9, 12, and 13 are in non-full loading.

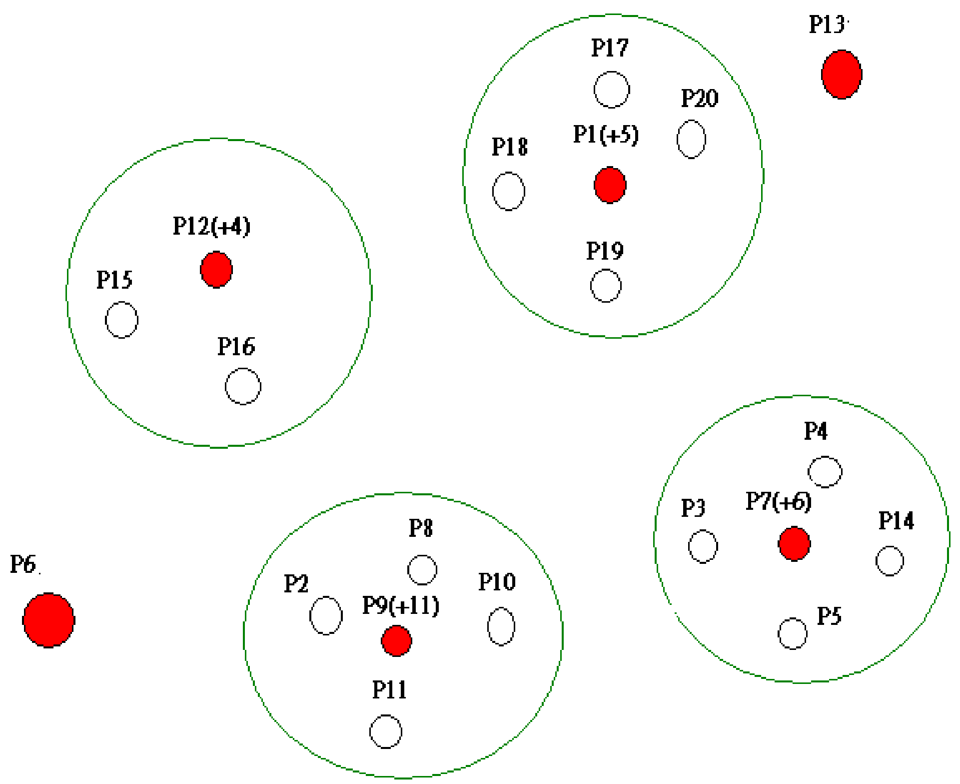

Figure 5. Modules formed by the atomic theory method for the motor system in Figure 4

For the non-full loading atoms, if two or more atoms can be combined into a full loading atom by keeping the largest positively charged atomic nucleus and changing the other merged atomic nuclei to negatively charged electrons, the number of modules in the product will be reduced and the connections between the modules will be simpler. For example, in Figure 5, if the modules associated with parts 7, 9, 13 (or parts 7, 9, 6) are combined, by keeping part 9 a positively charged nucleus and changing parts 9 and 13 (or 9 and 6) into a new negative electron, the three non-full loading atoms become one full loading atom.

5.1.8 Result Discussion

From the results, parts 7 and 14 are in the same module. Part 7 is a worm and part 14 is a worm gear. However, from the original design, it’s apparent that, during the assembly process, parts 7 and 14 are difficult to assemble because part 14 needs to be inserted through the holes in parts 12 and 9 to be joined to part 7. Thus, designers should strive to redesign the module to improve assemblability of the given product. For example, parts 9 and 12 can be redesigned by removing material above the lower half of the holes, so that the worm and worm gear could be assembled from the same direction, e.g., lowered from above the holes.

5.2 A Table Lamp

In the following case study, we apply the developed method to a table lamp design which was used by Tseng, Chang, and Li [14] and compare our results with their method. There are twenty-two parts in the table lamp, as show in Figure 6.

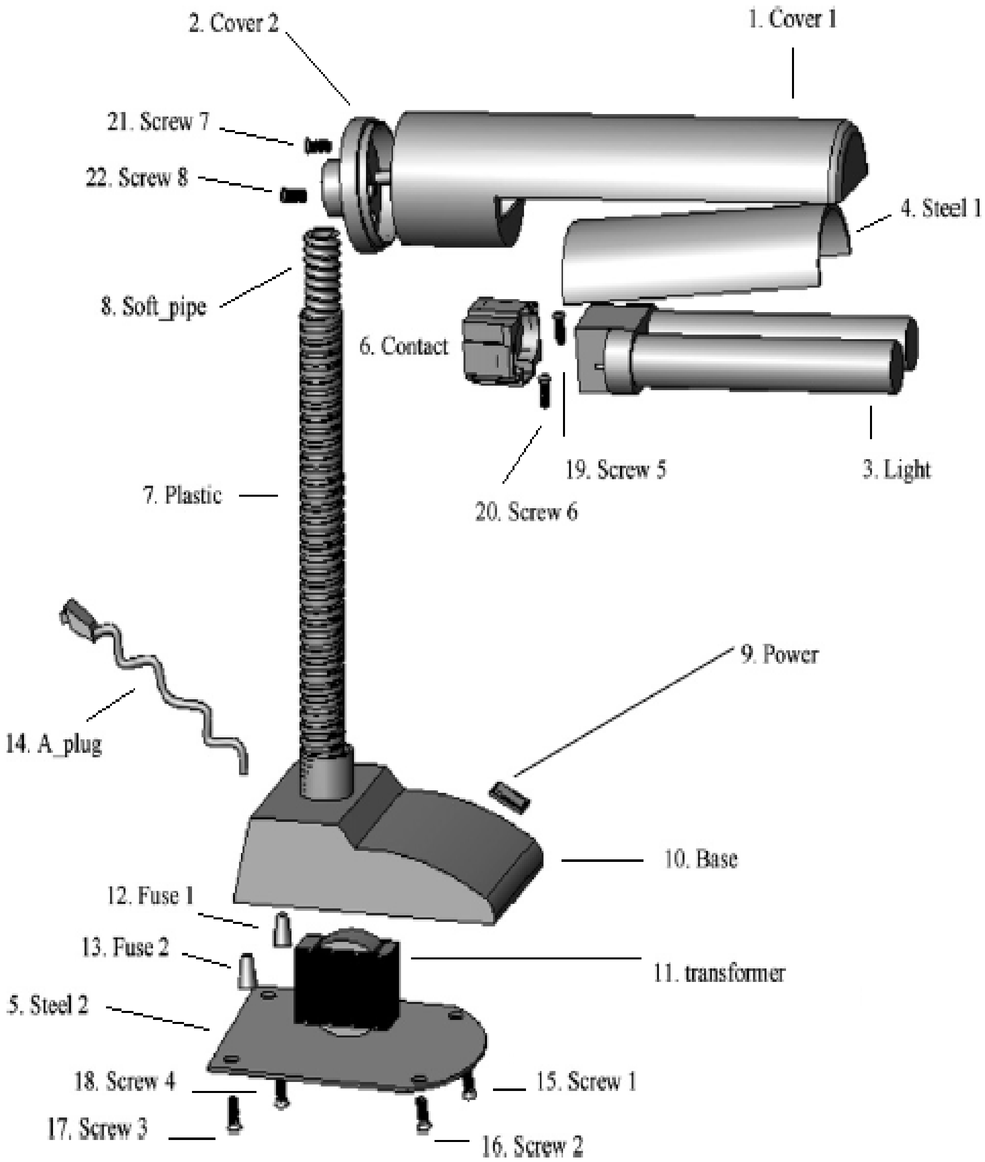

Figure 6. A table lamp

5.2.1 Touch Matrix

With our method, product design engineers can decide on the approximate number of positively charged atomic nuclei (modules) they would like in their final design, based upon product and module requirements. If they choose more positively charged atomic nuclei, more modules are formed. Working as product design engineers, for the given case study, we decided that any parts with more than three touching relationships would be chosen to be positively charged atomic nuclei.

5.2.2 Total Touch Matrix and Valence Matrix

The resulting Touch matrix *T* is shown in Table 8. Total Touch matrix *TT* and Valence matrix *Q* are shown as follows. Here, we set the threshold value as three. Thus, there are six positively charged atomic nuclei which touch more than three parts, which are parts 1, 2, 5, 6, 10, and 14. The rest of the parts were assigned to be negatively charged electrons.

Table 8. Touch matrix, for product in Figure 6

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1	0	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1
3	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
4	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1	1	1	0	0	0	0
6	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0
7	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0
8	0	1	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	1	0	1	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0
15	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

$$TT = \begin{bmatrix} 5 \\ 4 \\ 3 \\ 1 \\ 5 \\ 4 \\ 2 \\ 3 \\ 1 \\ 9 \\ 1 \\ 1 \\ 1 \\ 4 \\ 2 \\ 2 \\ 2 \\ 2 \\ 2 \\ 2 \\ 2 \\ 2 \end{bmatrix} \qquad Q = \begin{bmatrix} +5 \\ +4 \\ -1 \\ -1 \\ +5 \\ +4 \\ -1 \\ -1 \\ -1 \\ +9 \\ -1 \\ -1 \\ -1 \\ +4 \\ -1 \\ -1 \\ -1 \\ -1 \\ -1 \\ -1 \\ -1 \\ -1 \end{bmatrix}$$

5.2.3 Distance Matrix

The product includes eight fasteners (parts 15-22), and its *Distance matrix*, *D,* is shown in Table 9.

5.2.4 Force Matrix

From the *Valence matrix Q*, we know that parts 1, 2, 5, 6, 10 and 14 are positively charged atomic nuclei and the rest of the parts are negatively charged electrons. The *k* value in Equation 2 is generally set to be one. However, when some positively charged atomic nuclei have the same valence value, in *Valence matrix Q*, the value of k is increased sequentially for the given parts. Since parts 1 and 5 have the same valence value of 5, k_1 is 1 and k_5 is 2. Similarly, parts 2, 6, and 14 have the same valence of 4. Thus, k_2 is 1, k_6 is 2, and k_{14} is 3. Finally, the *Force matrix F* can be easily calculated. For example, the force between parts 1 and 6 is $F_{16} = -\frac{k_1 k_6 Q_1 Q_6}{D_{16}^{\ 2}} = -\frac{1 \times 2 \times (+5) \times (+4)}{1^2} = -40$. Finally, the *Force matrix* of this case study is shown in Table 10.

Table 9. Distance matrix for product in Figure 6

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1	0	1	2	1	2	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
2	1	0	2	2	2	2	2	1	2	2	2	2	2	2	2	2	2	2	2	2	1	1
3	2	2	0	2	2	1	2	2	2	2	2	2	2	2	2	2	2	2	2	1	2	2
4	1	2	2	0	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
5	2	2	2	2	0	2	2	2	2	1	2	2	2	2	1	1	1	1	2	2	2	2
6	1	2	1	2	2	0	2	2	2	2	2	2	2	2	2	2	2	2	1	1	2	2
7	2	2	2	2	2	2	0	1	2	1	2	2	2	2	2	2	2	2	2	2	2	2
8	2	1	2	2	2	2	1	0	2	1	2	2	2	2	2	2	2	2	2	2	2	2
9	2	2	2	2	2	2	2	2	0	1	2	2	2	2	2	2	2	2	2	2	2	2
10	2	2	2	2	1	2	1	1	1	0	2	2	2	1	2	2	2	2	2	2	2	2
11	2	2	2	2	2	2	2	2	2	2	0	2	2	1	2	2	2	2	2	2	2	2
12	2	2	2	2	2	2	2	2	2	2	2	0	2	1	2	2	2	2	2	2	2	2
13	2	2	2	2	2	2	2	2	2	2	2	2	0	1	2	2	2	2	2	2	2	2
14	2	2	2	2	2	2	2	2	2	1	1	1	1	0	2	2	2	2	2	2	2	2
15	2	2	2	2	1	2	2	2	2	2	2	2	2	2	0	2	2	2	2	2	2	2
16	2	2	2	2	1	2	2	2	2	2	2	2	2	2	2	0	2	2	2	2	2	2
17	2	2	2	2	1	2	2	2	2	2	2	2	2	2	2	2	0	2	2	2	2	2
18	2	2	2	2	1	2	2	2	2	2	2	2	2	2	2	2	2	0	2	2	2	2
19	2	2	2	2	2	1	2	2	2	2	2	2	2	2	2	2	2	2	0	2	2	2
20	2	2	2	2	2	1	2	2	2	2	2	2	2	2	2	2	2	2	2	0	2	2
21	2	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	0	2
22	2	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	0

Table 10. Force matrix for product in Figure 6

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1	0	-20	1.25	5	-12.5	-40	1.25	1.25	1.25	-11.3	1.25	1.25	1.25	-15	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25
2	-20	0	1	1	-10	-8	1	4	1	-9	1	1	1	-12	1	1	1	1	1	1	4	4
3	1.25	1	0	-0.25	2.5	8	-0.25	-0.25	-0.25	2.25	-0.25	-0.25	-0.25	3	-0.25	-0.25	-0.25	-0.25	-0.25	-1	-0.25	-0.25
4	5	1	-0.25	0	2.5	2	-0.25	-0.25	-0.25	2.25	-0.25	-0.25	-0.25	3	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25
5	-12.5	-10	2.5	2.5	0	-20	2.5	2.5	2.5	-90	2.5	2.5	2.5	-30	10	10	10	10	2.5	2.5	2.5	2.5
6	-40	-8	8	2	-20	0	2	2	2	-18	2	2	2	-24	2	2	2	2	8	8	2	2
7	1.25	1	-0.25	-0.25	2.5	2	0	-1	-0.25	9	-0.25	-0.25	-0.25	3	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25
8	1.25	4	-0.25	-0.25	2.5	2	-1	0	-0.25	9	-0.25	-0.25	-0.25	3	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25
9	1.25	1	-0.25	-0.25	2.5	2	-0.25	-0.25	0	9	-0.25	-0.25	-0.25	3	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25
10	-11.3	-9	2.25	2.25	-90	-18	9	9	9	0	2.25	2.25	2.25	-108	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25
11	1.25	1	-0.25	-0.25	2.5	2	-0.25	-0.25	-0.25	2.25	0	-0.25	-0.25	12	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25
12	1.25	1	-0.25	-0.25	2.5	2	-0.25	-0.25	-0.25	2.25	-0.25	0	-0.25	12	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25
13	1.25	1	-0.25	-0.25	2.5	2	-0.25	-0.25	-0.25	2.25	-0.25	-0.25	0	12	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25
14	-15	-12	3	3	-30	-24	3	3	3	-108	12	12	12	0	3	3	3	3	3	3	3	3
15	1.25	1	-0.25	-0.25	10	2	-0.25	-0.25	-0.25	2.25	-0.25	-0.25	-0.25	3	0	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25
16	1.25	1	-0.25	-0.25	10	2	-0.25	-0.25	-0.25	2.25	-0.25	-0.25	-0.25	3	-0.25	0	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25
17	1.25	1	-0.25	-0.25	10	2	-0.25	-0.25	-0.25	2.25	-0.25	-0.25	-0.25	3	-0.25	-0.25	0	-0.25	-0.25	-0.25	-0.25	-0.25
18	1.25	1	-0.25	-0.25	10	2	-0.25	-0.25	-0.25	2.25	-0.25	-0.25	-0.25	3	-0.25	-0.25	-0.25	0	-0.25	-0.25	-0.25	-0.25
19	1.25	1	-0.25	-0.25	2.5	8	-0.25	-0.25	-0.25	2.25	-0.25	-0.25	-0.25	3	-0.25	-0.25	-0.25	-0.25	0	-0.25	-0.25	-0.25
20	1.25	1	-1	-0.25	2.5	8	-0.25	-0.25	-0.25	2.25	-0.25	-0.25	-0.25	3	-0.25	-0.25	-0.25	-0.25	-0.25	0	-0.25	-0.25
21	1.25	4	-0.25	-0.25	2.5	2	-0.25	-0.25	-0.25	2.25	-0.25	-0.25	-0.25	3	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25	0	-0.25
22	1.25	4	-0.25	-0.25	2.5	2	-0.25	-0.25	-0.25	2.25	-0.25	-0.25	-0.25	3	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25	0

5.2.5 Maximum Force Matrix

From the *Force matrix*, the *Maximum Force matrix*, *MF*, can be obtained:

$$MF = \begin{bmatrix} +5 \\ +4 \\ +8 \\ +5 \\ +10 \\ +8 \\ +9 \\ +9 \\ +9 \\ +9 \\ +12 \\ +12 \\ +12 \\ +12 \\ +10 \\ +10 \\ +10 \\ +10 \\ +8 \\ +8 \\ +4 \\ +4 \end{bmatrix}$$

From the *Maximum Force matrix*, we know that [MF_1, MF_4] = +5, [MF_2, MF_{21}, MF_{22}] = +4, [MF_3, MF_6, MF_{19}, MF_{20}] = +8, [MF_7, MF_8, MF_9, MF_{10}] = +9, [MF_5, MF_{15}, MF_{16}, MF_{17}, MF_{18}] = +10, and [MF_{11}, MF_{12}, MF_{13}, MF_{14}] = +12. Thus, the resulting modules are [1,4], [2,21,22], [3,6,19,20], [7,8,9,10], [5,15,16,17,18], [11,12,13,14], as shown in Figure 6.

5.2.6 Green product design

In this case study, if part 3 (light) needs to be recycled then its disassembly time and disassembly difficulty need to be reduced. If we chose to integrate the desired green constraints into the original product modules, the *Distance matrix* which integrates the green constraints will be as shown in Table 11.

Table 11. The Distance matrix of the recyclable constraints for product in Figure 7

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1	0	1	2	1	2	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
2	1	0	2	2	2	2	2	1	2	2	2	2	2	2	2	2	2	2	2	2	1	1
3	2	2	0	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	2	2
4	1	2	2	0	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
5	2	2	2	2	0	2	2	2	2	1	2	2	2	2	1	1	1	1	2	2	2	2
6	1	2	2	2	2	0	2	2	2	2	2	2	2	2	2	2	2	2	1	1	2	2
7	2	2	2	2	2	2	0	1	2	1	2	2	2	2	2	2	2	2	2	2	2	2
8	2	1	2	2	2	2	1	0	2	1	2	2	2	2	2	2	2	2	2	2	2	2
9	2	2	2	2	2	2	2	2	0	1	2	2	2	2	2	2	2	2	2	2	2	2
10	2	2	2	2	1	2	1	1	1	0	2	2	2	1	2	2	2	2	2	2	2	2
11	2	2	2	2	2	2	2	2	2	2	0	2	2	1	2	2	2	2	2	2	2	2
12	2	2	2	2	2	2	2	2	2	2	2	0	2	1	2	2	2	2	2	2	2	2
13	2	2	2	2	2	2	2	2	2	2	2	2	0	1	2	2	2	2	2	2	2	2
14	2	2	2	2	2	2	2	2	2	1	1	1	1	0	2	2	2	2	2	2	2	2
15	2	2	2	2	1	2	2	2	2	2	2	2	2	2	0	2	2	2	2	2	2	2
16	2	2	2	2	1	2	2	2	2	2	2	2	2	2	2	0	2	2	2	2	2	2
17	2	2	2	2	1	2	2	2	2	2	2	2	2	2	2	2	0	2	2	2	2	2
18	2	2	2	2	1	2	2	2	2	2	2	2	2	2	2	2	2	0	2	2	2	2
19	2	2	2	2	2	1	2	2	2	2	2	2	2	2	2	2	2	2	0	2	2	2
20	2	2	2	2	2	1	2	2	2	2	2	2	2	2	2	2	2	2	2	0	2	2
21	2	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	0	2
22	2	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	0

Following the same procedure, we can create green modules based on the *Distance matrix.* The results are shown in Table 12. Product design engineers can then compare differences between the original modules and the green modules for product redesign and improvement. Since part 3 (light) needs to be recycled, product design engineers can make the part an individual module in the green design, and [6, 19, 20] another module. In addition, in module [6, 19, 20], the two screws (parts 19 and 20) could also be eliminated to make part 3 (light) easier and quicker to replace. Module [1, 4] and [2, 21, 22] could also be redesigned and simplified to make part 3 easier to remove. Similarly, module [5, 15, 16, 17, 18] could be redesigned to reduce the number of screws and thereby make the product easier to disassemble.

Table 12. The original structure modules and the recycle modules

Structure modules	[1,4], [2,21,22], [3,6,19,20], [7,8,9,10], [5,15,16,17,18], [11,12,13,14]
Recycle modules	[1,4], [2,21,22], [6,19,20], [7,8,9,10], [5,15,16,17,18], [11,12,13,14], [3]

We used the green contribution value to evaluate each one of modules. In the second case, the *Green Contribution* contains *Modular Index and Recycle Index*. For convenience, we assume the net weight of each part is 1 kg.

(1) Structure Modules: [1,4], [2,21,22], [3,6,19,20], [7,8,9,10], [5,15,16,17,18], [11,12,13,14]

Modular Index $= 1 - \frac{6}{22} = 0.73$

Recycle Index $= (0 + 0 + \frac{1}{4} + 0 + 0 + 0) = 0.25$

Green Contribution = 0.73+0.25 = 0.98

(2) Recycle Modules: [1,4], [2,21,22], [6,19,20], [7,8,9,10], [5,15,16,17,18], [11,12,13,14], [3]

Modular Index $= 1 - \frac{7}{22} = 0.682$

Recycle Index $= (0 + 0 + 0 + 0 + 0 + 0 + 1) = 1$

Green Contribution = 0.682+1 = 1.682

The product design engineers can choose modules based on the green contribution value. After adding the recyclable constraints, we can find that the green product design is better than the non-green product design from the value of green contribution.

5.2.7 Merging

If a module has only one connection relationship with another module, the disassembly time and disassembly difficulty is minimized, which is considered to be the best case for modular design. Therefore, an atom meets the best condition if the total sum of the positive charges and negative charges in the atom is one. We define this condition as “full loading”. A total which is not one implies that the module has more than one touching relationship with other adjacent modules, and the module is in a “non-full loading” condition. In this case study, parts 5, 6 and 14 are in full loading, and parts 10, 2 and 1 are in non-full loading.

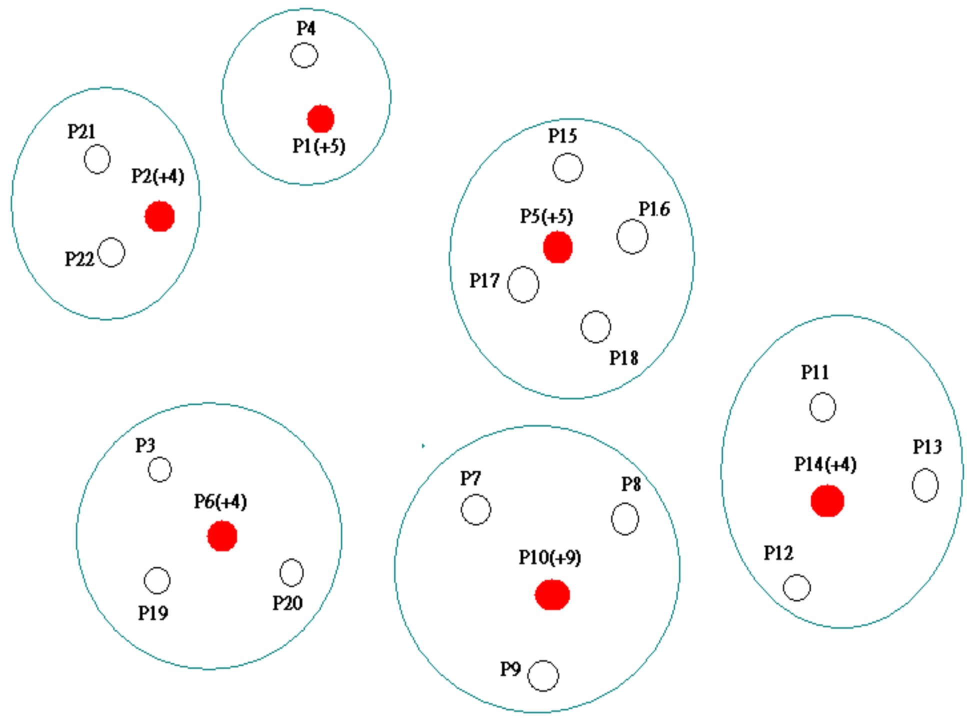

Figure 7. Modules formed by the atomic theory method for the table lamp in Figure 6

For the non-full loading atoms, if two atoms can be combined into a full loading atom by changing one of the atomic nuclei to a negatively charged electron, the number of modules in the product will be reduced and the connections between the modules will be simpler. For example, in Figure 9, if the two modules associated with part 1 and part 2 are combined, by keeping part 1 a positively charged nucleus and changing part 2 into a new negative electron, the two non-full loading atoms become one full loading atom.

After merging, the resulting modules for the table lamp case study design are shown in Table 13. For the given case study, solution 2 is the same as the solution found using the method developed by Tseng, Chang and Li [14]. In their approach, they used GGAs to find modules for the table lamp.

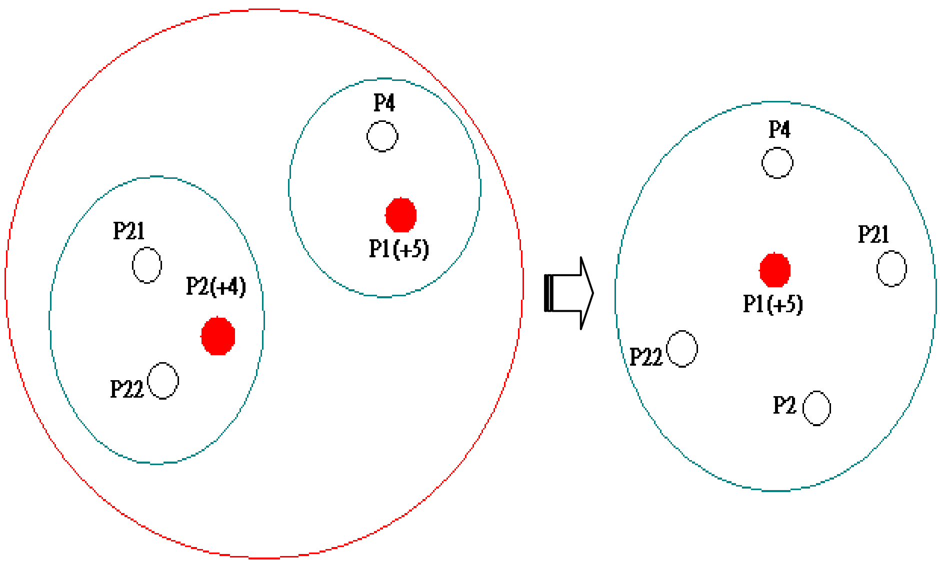

Figure 8. Merging two non-full loading atoms into a single full loading atom

Table 13. Module results for the table lamp case study

Solutions	Resulting Modules (Structure Modules)	Module Number	Green Contribution
Solution 1	[1,4], [2,21,22], [3,6,19,20], [7,8,9,10], [5,15,16,17,18], [11,12,13,14]	6	0.73
Solution 2 (after merging)	[1,2,4,21,22], [3,6,19,20], [7,8,9,10], [5,15,16,17,18], [11,12,13,14]	5	0.77
Solution 3 (after merging)	[1,2,4,7,8,9,10,21,22], [3,6,19,20] , [5,15,16,17,18], [11,12,13,14]	4	0.81

5.2.8 Result Discussion

In the case study, we apply the developed method to a table lamp design which was used by Tseng, Chang, and Li [14]. We not only have the same results of modules but also get more types of modules by merging. In addition, we can add design constraints in our product. If design engineers need to do green product design, they just need to add green considerations into their design constraints.

This case study shows that the developed method is a practical and efficient approach for developing green product designs. With our proposed atomic theory-based green product design method, problems with prior methods obtaining unrealistic solutions can be avoided. Because all type of modules come from the original modules which based on their touch relationships, it can make sure the structure in the product is reasonable and practical. Our innovation method can also help design engineers examine the original design for further redesign.

Chapter 6. Conclusions

This thesis presents an innovative method for green product design by atomic theory. The developed method can provide product design engineers more control and finer sensitivity with respect to green design constraints in the initial stage of product life-cycle design. Study results show that the developed method is a practical and efficient approach for developing green product modular design. With our proposed atomic theory-based product modular design method, problems with prior methods obtaining unrealistic solutions can be avoided. The proposed method can also be easily applied to different kinds of products. Product design engineers only need to build a touch matrix and define green constraints. Product design engineers can establish a desired number of modules by selecting the minimum number of positive charges which will form atomic nuclei. Different module solutions can be developed and considered by merging non-full loading modules. The developed method can not only produce product modules but also provide design engineers a flexible way to add green design constraints. Different types of modules can be produced, based on the different green constraints. Product design engineers can compare and choose which module type is more suitable for the product requirements through module selections and evaluations. In addition, green product design in the initial product life-cycle stage can control the recycle rate or reuse rate of the product meet the environmental regulations. Since most contemporary CAD systems can quickly calculate the net weight of parts, it can help product design engineers calculate the design indices and predict whether the products conform the environmental regulations or not. Therefore, the developed method can make products more competitive and sustainable in the global market.

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