sustainability

MDPI

Article

Modeling an Innovative Green Design Method for Sustainable Products

Yao-Tsung Ko

Department of Industrial Design, Tunghai University, Taichung City 40704, Taiwan; mike.ko@thu.edu.tw

Received: 14 March 2020; Accepted: 17 April 2020; Published: 20 April 2020

check for updates

Abstract: Global warming and climate change are currently the world's most pressing issues. The causes are the results of people pursuing a better quality of life and a material civilization. Thus, if the concept of green design can be applied when designing and manufacturing products, it will greatly reduce the environment impact of such production. This paper addresses a novel green design method based on the extension theory and concept of Green DNAs, which embraces the concepts of green technology, green material, and green manufacturing. The proposed method can provide designers with a decomposing–recomposing approach with rigorous logic and deduction processes for transforming general products into green products. It can also facilitate the use of green modular approaches in product design and improve product disassembly to raise the value added by product recycling. It offers companies concrete guidance and detailed steps to apply in green product design. Finally, a practical green product design of a medical air purifier is demonstrated to validate the feasibility and effectiveness of the proposed method.

Keywords: green design method; extension theory; Green DNAs; green modular; sustainable product

1. Introduction

Environmental issues have long been of concern to the design community. As early as the 1970s, Papanek [1] advocated sustainable design to protect the environment. Kurk and Eagan [2] also applied the power of industrial design to propose green products for people in third-world countries, trying to improve the lives of those who live at the lowest end of the pyramid of consumption using the methods of green design. In 2007, the National Design Museum in New York held an exhibition called "Design for the Other 90%". This mainly showed how product design can help solve problems such as education, energy, water, health, sanitation, housing, and transportation. It also demonstrated many outstanding green design works, and the results were significant, as they attracted more interested to design in relation to social issues. Green design is an approach which can reduce the environmental impact of products to facilitate the sustainable development of the society. In the years since, how the power of green design can be used to reduce the impact of products on the environment has become an ever more important issue for the sustainable survival of mankind.

With the increase of environmental awareness and the establishment of environmental protection laws, green product design not only plays a critical role in the manufacturing industry, but has also become a main focal point in the future [3,4]. Consumers' requirements are no longer met only by functional and industrial design, as they now also consider whether products conform to environmental principles and regulations. In addition, the implementation and promotion of environmental laws has made green product design a necessary practice for industries in many countries [5]. Therefore, it is necessary for product designers to take into account environmental impacts and green factors in the initial stages of the product design lifecycle. This can help ensure that products comply with environmental principles, facilitate subsequent product maintenance and disassembly, and improve product reuse, recycling, and regeneration.

The design method plays an important role in the process of designing and developing products, and is a key tool in determining whether an item can successfully become a green product or not. In general, design methods are related to the way designers work, and can be interpreted as a mechanism for applying systematic concepts to innovative design [6], built up by insighting, ideating, prototyping, and evaluating processes to find the best ideas for the final design resolutions [7]. Design methods can be vital tools that can provide designers with specific guidance and steps to create new possibilities, and to provide new options and new solutions for products [8]. Some authors [9,10] have also focused on creating green design methods to assist designers in green product design and development.

The extension method [11] can provide an innovative green design method by decomposing and recomposing a system or product. It has rigorous deconstruction methods and logic, which can help product designers construct innovative green concepts in the early stages of product design. This paper thus aims at proposing an innovative green design method based on the extension method and Green DNAs. An effective and feasible design approach is therefore provided to designers for creating practical green products.

The paper is structured as follows: Section 2 presents a literature review of the main definitions and classifications of green products and related works, whereas Section 3 proposes a new green design method and the concept of Green DNAs, which represent detailed design processes for designers to follow when developing green products. In Section 4, the practical design of a medical air purifier is demonstrated to validate the feasibility and effectiveness of the proposed approach with regard to sustainability, while in Section 5, the results and discussions of the prototype of the green product created by the proposed green design method are provided. Finally, Section 6 reports the conclusions.

2. Related Works of Green Product Design

Today, becoming "green" is both a trend and an opportunity for companies. There are many reasons for this, such as competitiveness, the related laws, and corporate social responsibility (CSR) [12,13]. Many companies are thus trying to incorporate the factors of environmental sustainability into their product design [14]. In this atmosphere, the design and development of green products has become more and more important, and this is reflected in both practice and the literature [15,16]. In particular, green product design is attracting more interest as a means to enhance company performance and competitiveness [17]. However, there is still much debate about the definition of green products [18], and many uncertainties about which green factors companies should consider when developing such products.

2.1. Definitions and Classifications of Green Products

In terms of sustainability, multiple meanings of the word "green" have been explained and discussed in the literature [19,20]. In particular, McDonagh and Prothero [20] define several dimensions of "green", embracing economics, society, industry, ecology, profit, consumer, trade, equality, and sustainability. These concepts are very wide and involve many levels, but these "green" meanings have also caused confusion for many firms and cannot provide a clear guidance for those wanting to become greener, and there are many descriptions that aim to identify what green products are [21]. Moreover, there are still concerns about the green factors that construct eco-friendly products [22]. With regard to the various characteristics and definitions of green products, the European Commission [23] defines them as those that use less energy and resources, have lower environmental impacts and risks, and prevent waste generation during the early product design phase. This definition emphasizes the importance of designing products as "green" from the initial conceptualization phase on, and that even here they have "green" attributes. Overall, this is the best definition of green product design.

2.2. Green DNAs

Some researchers [24–26] have attempted to further define "green products". Ottman et al. [27] addresses the main aspects of green product development to reduce the environmental impact of such activities, including in terms of energy, material, waste, and pollution. Shrivastava [28] states that the limits of the natural environment will drive existing products towards becoming green products with better energy efficiency and less material usage. Kaebernick and Soriano [29] adopt a simple method to evaluate the green products and classify them based on their environmental characteristics. They use two factors of energy and material to measure the environmental impact of products in the four stages of their life cycles, namely material, manufacture, use, and disposal. Dewberry and Goggin [30] propose an Ecodesign Matrix to distinguish the environmental impact of products based on two dimensions, including life cycle and environmental focus. The evaluating factors embrace process, use, and disposal in the life cycle factors, and energy, material, pollution, and waste in the environmental focus. Most problems related to adverse environmental impact are due to energy, material, process, use, disposal, pollution, and waste, all of which can be addressed through the use of green technology, green materials, and green manufacturing. As such, this study defines these three factors as the three Green DNAs of green products.

2.3. Green Design Methods

In the past, some green design methods have been developed to help designers reduce the environmental impacts of their products [31–33]. Eastwood and Haapala [34] propose an aggregation method to help designers produce three alternative bevel gear designs at the manufacturing stage based on the eco-design concept. A lot of researchers apply the Theory of Inventive Problem Solving (TRIZ) to create an innovative eco-design method for green products [35,36]. Mann [37] proposes a systematic sustainable innovation approach for sustainable products, services, and the product–service system based on TRIZ. Some authors integrate TRIZ with other methods to propose eco-innovative approaches such as Quality Function Deployment (QFD), Lean, the Taguchi method, Failure Mode and Effects Analysis (FMEA), the Analytic Hierarchy Process (AHP), Kano, Axiomatic Design, and so on [38,39]. Chen and Liu [40,41] present a successful combination of eco-efficiency elements and the 39 TRIZ engineering parameters, along with a series of eco-design methods. Chang and Chen [42] also present some eco-innovative design methods and green evolution rules based on TRIZ and the design around approach.

The TRIZ method [43] is a useful tool for designers to deal with the conflicts that can arise in the process of solving design problems. The TRIZ method was first proposed by Altshuller [44], based in the former Soviet Union, who analyzed more than 300,000 patents to establish a contradiction matrix with 39 engineering parameters and 40 invention principles. In order to use the TRIZ method in problem solving in innovative design, designers need to first discover the corresponding contradictions for their current design problems. Secondly, designers have to match the meaning of each design problem with two appropriate parameters from among 39 engineering parameters defined in the TRIZ contradiction matrix. After determining the contradiction parameters, the designers can find the most commonly used principles among the corresponding 40 kinds of invention principles from the TRIZ contradiction matrix. However, during this analysis, a problem that designers often encounter is the inability to quickly and correctly convert design problems into corresponding engineering parameters. Indeed, this is the main problem when designers apply TRIZ to solve design problems.

2.4. Green Modular and Product Disassembly for Sustainability

The manufacturing industry is facing the challenge of how to create a product with less impact on the environment for a more sustainable society, and green design plays a critical role in this. Green product design is defined as the practical application of factors that can reduce the environmental impact of products during the design phase. Some design methods have been proposed for green product design, such as design for modular (DFM), design for disassembly (DFD), and design for regeneration (DFR). DFM is further extended to "design for green modular". Because this can improve the environmental effectiveness of products, green modular design is now regarded as an important design method.

In recent years, many studies have thus been conducted in the field of green modular design. Ishii [45] proposes the concept of "technical modular", which uses "cluster" analysis to connect "modularity" with "product retirement design". The goal of the "technical module" is to group components with the same method of retirement into the same module. Huang et al. [46] adopted five basic rules for recycling in a modular design. These embrace the environmental impact of recycling, material compatibility, life cycle analysis, recycling profits, and an analysis of structural and physical interactions. Gu and Sosale [47] consider the needs of the entire product life cycle and studied modular design methods. Umeda et al. [48] propose a modular design method that develops the optimal design of a modular structure based on life cycle attributes and geometric information. Tseng et al. [49] use a grouped genetic algorithm to gather components into modules that support lifecycle engineering, with the resulting green modules derived based on green design factors. Considering the inclusion of green factors in the new module, Smith and Yen [50] present a green modular approach based on atomic theory, in which the green module is developed by combining or decomposing structural modules to reduce the environmental impacts.

There are many characteristics of "green" products, and design for disassembly (DFD) is one of the key factors. Disassembly is usually the first step in the recovery process. In particular, manufacturing design and recycling design are based on the concept of disassembly design [51]. Pnueli and Zussman [52] point out that only 10%–20% of the cost of product recycling depends on the product recycling process, and the rest is decided during the product design phase. Seo et al. [53] indicate that product disassembly has a strong relationship with the cost of the product lifecycle. Prior research also shows that product disassembly is the last and most important process before the operations of the product's value-added recovery [54]. Therefore, product disassembly will directly influence the entire product value and sustainability [51].

Some prior research adopts advanced searching algorithms to discover the best sequences of product disassembly. Aguinaga et al. [55] employ a method using fast-growing random trees to find the best product disassembly sequences. Kara et al. [56] propose an approach to derive reversed assembly sequences, and utilize a liaison diagram to evaluate geometric connections in order to find the optimal disassembly sequences of a product. However, this method requires a lot of computing resources to generate sequence diagrams, and the infeasible sequences must be removed in the process. Shyamsundar and Gadh [57] present a regressive approach that takes into account both the separating direction and decomposing direction to disassemble the components of the target product. However, these approaches lead to many paths, so it takes a lot of time to find a solution. Moreover, neither the time needed nor outcomes obtained can be guaranteed. Furthermore, the resulting sequences are often not optimal solutions and usually include interfering elements. Most of the studies discussed above address the problem of product disassembly by considering all geometric limitations and evaluating each disassembly order to discover the best solution.

Although many studies can be found of green modular design and disassembly for recycling, traditional green modular design and product disassembly design have the drawback of lacking overall and comprehensive green design considerations. They just cannot be used to develop the most sustainable benefits to products, including how to reduce energy consumption, use green materials, and apply green manufacturing. In today's highly competitive global market, products must be replaced at a faster rate than before. Innovative design methods are thus important and have been recognized and adopted by some companies because they have the benefits of improving the competitiveness of products and reducing the time to market.

From the brief review of the design methods presented above, we found that these innovative approaches have clear implementation steps, but they still have obvious problems in practical design, and cannot really assist companies in developing innovative green products. In particular, there are many special formulas and calculations proposed in these methods, which make them hard to apply in practical product design. The key point is that they cannot provide the exact processes needed for green design, as they only focus on green engineering modularization or green process assessments, and this is insufficient for green product design in practical applications. To overcome the limitations of prior methods, an innovative green design method is developed in the current study, which uses the concepts of the extension method and Green DNAs to solve the related design problems. From the viewpoint of practical design, the proposed innovative green design method can be regarded as a "decompose–generate–recompose" approach in the "divergence to convergence" process. In addition, it can provide an optimal solution for green product design by simultaneously considering the environmental impact of products and optimal product structure for green modular design and product disassembly design. This is the motivation behind this research to develop a framework that guides the designers to perform green analysis and synthesis procedures in new product development (NPD).

3. Methodology

This research is based on the extension method [11] to develop an innovative green design method approach for green products. The extension method is a type of systematic method that provides engineers and designers with some particular and effective approaches to solving problems. This theory was first proposed by a Chinese researcher, Wen Cai [11,58], based on the extension of things. So far, it has been widely applied in many fields, including engineering, design, economics, sociology, management, etc. [59–62]. The extension method can help designers and engineers decompose problems, analyze a series of contexts, recombine problems, and effectively find feasible solutions. The extension method embraces four main parts: The matter–element expansion, the transform method, the evaluation method, and the diamond-shaped thought method. The proposed innovative green design method was developed based on the matter–element extension and transforming method. The extension theory and method can provide designers with a decomposing and recomposing approach for green product design. This approach will also facilitate the development of green modular and product disassembly design for greater product sustainability.

3.1. Extension Theory and Method

The extension method is derived from extension theory, which is a type of science that focuses on the extension of things, the law of development, the method of adoption, and how to solve the contradictions among subjects. There are two main theoretical parts in this method, including the matter–element model and the extension set theory. The extension laws of matter–element and transformation rules of matter–element are included in the matter–element theory. Extension mathematics is based on extension sets, and is a qualitative and quantitative tool that enables the extension method to solve contradictory problems. This study mainly adopts two methods: The matter–element model and the basic matter–element transformation rules in the extension theory. The existing products or technologies are decomposed by using the concept of the matter–element model. This is done in order to develop a new matter–element model with basic matter–element transformation rules, and then to introduce new products or technologies.

3.2. Matter–Element Model

The concept of matter–element is the basis of extenics, and all of the subsequent transformations are based on the matter–element concept. A matter–element is composed of the name of the thing (Name, N), the characteristic (Characteristic, C), and the value (Value, V). The matter–element is represented by R or r. The logical mathematical equation can be represented as follows [11]:

$$R = (N, C, V) \quad (1)$$

Everything in the world can be built as a matter–element model based on the above definition, including actual objects and abstract descriptions. The features and corresponding magnitudes in the matter–element model are not limited to one type, and can also be multiple representations. They can be qualitative and quantified in one matter–element model. The description can be any adjective or adverb. The characteristics and their corresponding values can be represented by multiple features and their corresponding values in the matter–element model. It is called an "n-dimensional matter–element", and its logical mathematical expression can be represented as follows [58]:

$$R = \begin{bmatrix} N & C_1 & V_1 \\ & C_2 & V_2 \\ & \vdots & \vdots \\ & C_n & V_n \end{bmatrix} = \begin{bmatrix} R_1 \\ R_2 \\ \vdots \\ R_n \end{bmatrix} \quad (2)$$

This study employs the concept of a matter–element model to build a product or technology decomposition system. According to its characteristics or attributes, any product or technology can be built as the first level of the matter–element model. Based on the main function, it is divided into subsystems, and then the second level of the matter–element model is established. The designated steps are then followed to establish all subsequent levels. The operation processes of the entire product are as shown in sequence in Figure 1 [11].

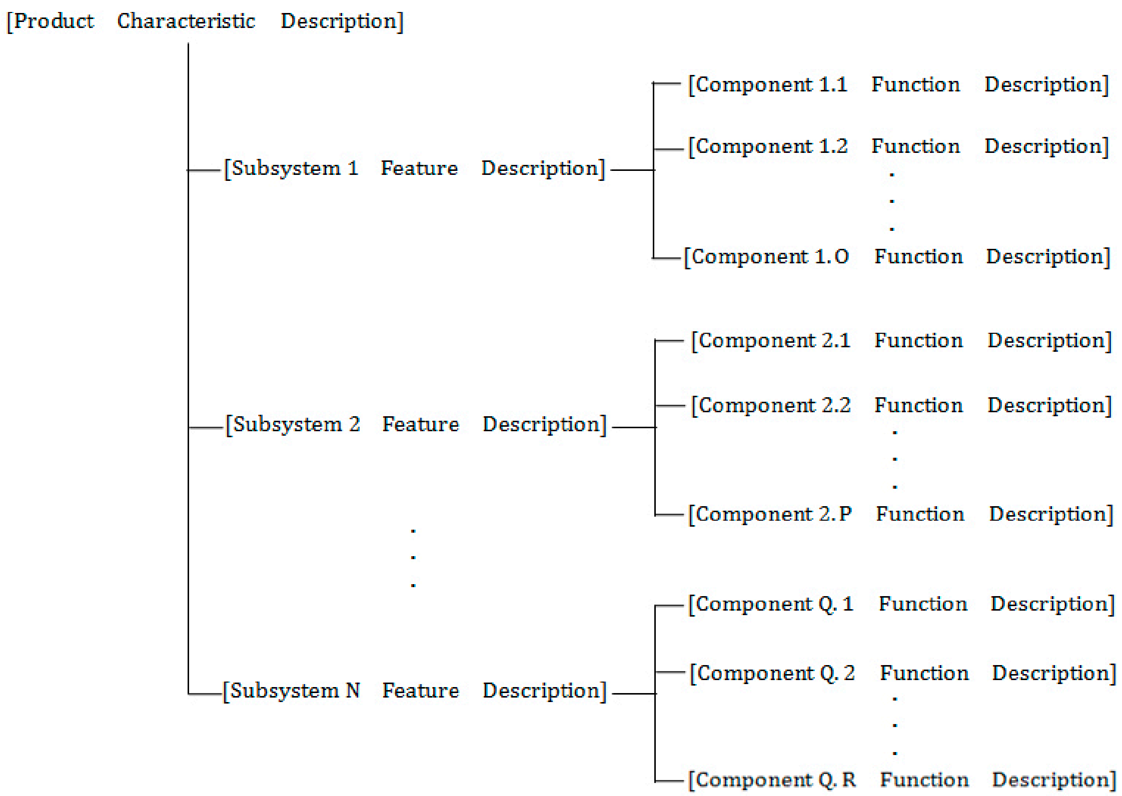

Figure 1. Build the decomposition system of products based on the matter–element model.

Any design problems can also be transformed into a corresponding matter–element model to facilitate the subsequent matter–element transformation and find the best solution. Therefore, when developing new products, it is possible to design innovative ones by establishing a decomposition system based on the matter–element model to find the improved parts of the products.

3.2.1. Extendibility of Matter–Element

Cai [11] proposed five extendibilities of the matter–element approach, including divergence, conjugation, correlation, implication, and expandability. Based on the dimensions of the matters, including the outward, inward, parallel, flexible, combining, and decomposite, it is possible to derive the paths of multiple transformations, which become the basis for extending things and solving contradictory problems [59].

Divergence: One matter has many characteristics, and one characteristic is possessed by many matters. There are the concepts of "one matter possessing many features", "one feature existing in many matters", "one value existing in many matters", and "one element existing in many matters".

These concepts are called divergence. Conjugation: The internal structure of matters is another focus of solving contradictions. Through changes to the internal structure, sometimes contradictions can also be transformed into compatibilities. One matter has eight dimensions, including the real, virtual, hard, soft, explicit, latent, positive, and negative. Things can be more comprehensively recognized, and innovations can be created by the analysis of the eight conjugate dimensions of matters. Correlation: There may be dependent relationships existing in matters with characteristics existing in one matter as well as different matters.

Implication: If matter A is realized, then matter B must also be realized. Matter A is said to be implicated in matter B.

Expandability: A matter can be combined with other matters into a new matter, or it can be decomposed into new matters. These new matters have certain characteristics that do not belong to the original matters.

3.2.2. Basic Matter–Element Transformation

After establishing the matter–element model, the matter–element transformation can be carried out. The matter–element transformation is the change of the three elements (N, C, V) in the matter–element model to obtain a new matter–element. The different matter–elements can be connected to form an intertwined network of matter–elements through the transformation of matter–elements. Matter–element transformation is a unique way of working to replace or synthesize the different matter elements according to a specific feature or attribute. It is a model that assists in the development of ideas based on the logic that may arise from human thinking. In this paper, matter–element transformation can be regarded as the basic tool to solve the design contradictions. It can be used to transfer the "quality" and "quantity" between the matter elements, including the object name. The basic matter–element transformation can be represented in a mathematical equation as follows [58]:

$$T = \begin{bmatrix} N_T & C_{T1} & V_{T1} \\ & C_{T2} & V_{T2} \\ & C_{T3} & V_{T3} \\ & \vdots & \vdots \\ & C_{Tn} & V_{Tn} \end{bmatrix} = \begin{bmatrix} \text{Transformation} & \text{Dominated characteristic} & V_{T1} \\ & \text{Accepted characteristic} & V_{T2} \\ & \text{Transforming result} & V_{T3} \\ & \vdots & \vdots \\ & C_{Tn} & V_{Tn} \end{bmatrix} \quad (3)$$

where N_T means the name of the transformation, which represents the type of the transformation. That is, $N_T \in$ {replacement, decomposition/composition, addition/deletion, expansion/contraction}. C_{Tn} denotes the characteristics of the transformation, and V_{Tn} indicates the values of the parameters. V_{T1}, V_{T2}, and V_{T3} represent the dominated characteristic, accepted characteristic, and transforming result, respectively. The above transforming process is usually abbreviated as $TV_{T1} = V_{T3}$. There are four types of basic matter–element transformations, including replacement, decomposition/assembly, addition/deletion, and expansion/contraction, as follows [58,59]:

(1) Replacement Transformation

Replacement: $T_1R = R'$,

where

$$T_1 = \begin{bmatrix} \text{Replacement} & C_{T1} & R \\ & C_{T2} & R \\ & C_{T3} & R' \\ & \vdots & \vdots \end{bmatrix} \quad (4)$$

Symbol T_1 represents the execution of the replacement transformation. R is the original object, and R′ denotes the result after the transformation. R becomes R′ by the replacement transformation. The replacement transformation can replace the name, characteristics, and quantification of the object in the matter–element model according to specific requirements.

(2) Decomposition and Composition Transformation

Decomposition: $T_2R = R' = \{R_1, R_2, \ldots, R_n\}$, $R_1 \oplus R_2 \oplus \ldots \oplus R_n = R$,

where

$$T_2 = \begin{bmatrix} \text{Decomposition} & C_{T1} & R \\ & C_{T2} & R \\ & C_{T3} & \{R_1, R_2, \ldots, R_n\} \\ & \vdots & \vdots \end{bmatrix}. \quad (5)$$

Composition: $T_3R = R' = R_1 \oplus R_2 \oplus \ldots \oplus R_n$, $R = \{R_1, R_2, \ldots, R_n\}$,

where

$$T_3 = \begin{bmatrix} \text{Composition} & C_{T1} & R \\ & C_{T2} & R \\ & C_{T3} & R_1 \bigoplus R_2 \bigoplus \ldots \bigoplus R_n \\ & \vdots & \vdots \end{bmatrix}. \quad (6)$$

Symbols T_2 and T_3 denote the execution of the decomposition or composition transformation. R is the original object, and R′ indicates the result after the transformation. R becomes R′ by the decomposition or composition transformation. In the matter–element theory, things are divided into "polymerizable" or "compositive" attributes. The "polymerizable" matter–element usually refers to a more abstract synthesis, while the "compositive" matter–element refers to a more specific combination. Since there is a combination, there is decomposition.

(3) Addition/Deletion Transformation

Addition: $T_4R = R' = R \oplus R_1$,

where

$$T_4 = \begin{bmatrix} \text{Addition} & C_{T1} & R \\ & C_{T2} & R_1 \\ & C_{T3} & R \bigoplus R_1 \\ & \vdots & \vdots \end{bmatrix}. \quad (7)$$

Deletion: $T_4R = R' = R \ominus R_1$,

where

$$T_5 = \begin{bmatrix} \text{Addition} & C_{T1} & R \\ & C_{T2} & R_1 \\ & C_{T3} & R \ominus R_1 \\ & \vdots & \vdots \end{bmatrix}. \quad (8)$$

Symbols T_4 and T_5 mean the execution of the addition or deletion transformation. R is the original object, and R′ represents the result after the transformation. R becomes R′ by the addition or deletion transformation. If two (or more) things can be synthesized or integrated according to specific relationships, it is called "addition"; otherwise, it is called "deletion".

(4) Expansion/Contraction Transformation

Expansion: $T_6R = \alpha R = R'$,

where

$$T_6 = \begin{bmatrix} \text{Expansion/Contraction} & C_{T1} & R \\ & C_{T2} & \alpha \\ & C_{T3} & \alpha R \\ & \vdots & \vdots \end{bmatrix}. \quad (9)$$

Similarly, symbol T_6 denotes the execution of the expansion or contraction transformation. R is the original object. The coefficient α indicates the magnification of the expansion and contraction. When $\alpha > 1$, it represents expansion transformation. Otherwise, when $0 < \alpha < 1$, it denotes contraction transformation. R′ is the result after the transformation. R becomes R′ by the expansion or contraction transformation. The expansion and contraction transformation is mainly carried out to adjust the amount of value in a matter–element to fit another matter in a reasonable condition.

3.2.3. Extension Set

After defining the matter–element model, the possible matter–element transformation must be evaluated. This is done by the extension set. The extension set can be written as $\widetilde{S} = \{(x, y) \mid x \in D, y = f(x) \in R\}$, where D is the theoretic domain, R is the real number domain $(-\infty, +\infty)$, and y is called the degree of correlation. According to the size of y, the elements in the domain can be divided into three cases, which belong to $\widetilde{S}$, do not belong to $\widetilde{S}$, and for which the extension belongs to $\widetilde{S}$. Set all possible sets of matter–elements that can be obtained by transformation as the domain. Then, establish an extension set on the domain and use the extension method to solve the problem. The detailed definition of an extension set can be represented as follows [63]:

Let D be a domain of objects and let x be a generic element of D; then, an extension set $\widetilde{S}$ in D is defined as a set as follows:

$$\widetilde{S} = \{(x, y)\big| x \in D,\ y = f\ (x) \in (-\infty, +\infty)\}, \quad (10)$$

where $y = f(x)$ is called the correlation function of extension set $\widetilde{S}$. The extended relational function is defined to quantify the relationship between an element and set. The range of an extended relational function is $(-\infty, +\infty)$, which means that an element belongs to any set with a certain degree. An extension set $\widetilde{S}$ in D can be denoted by

$$\widetilde{S} = S^+ \cup H_0 \cup S^-, \quad (11)$$

where

$$S^+ = \{(x, y)\big| x \in D,\ y = f(x) > 0\}, \quad (12)$$

$$H_0 = \{(x, y)\big| x \in D,\ y = f(x) = 0\}, \quad (13)$$

$$S^- = \{(x, y)\big| x \in D,\ y = f(x) < 0\}, \quad (14)$$

where S^+ is called a positive domain in $\widetilde{S}$; it can describe the degrees to which x belongs to X_0 ($X_0 \in D$). S^- is called a negative domain in $\widetilde{S}$; it describes the degree to which x does not belong to X_0. H_0 is called a zero boundary.

3.3. Green DNAs

From the prior literature, we can find that the most eco-friendly products adopt green technology, green material, and green manufacturing to improve the green properties of the products. This study specifically defines these three green design factors as Green DNAs (Figure 2). In the processes of designing products in the future, if designers can carry out their design thinking based on the three Green DNAs, they should be able to obtain good green design results.

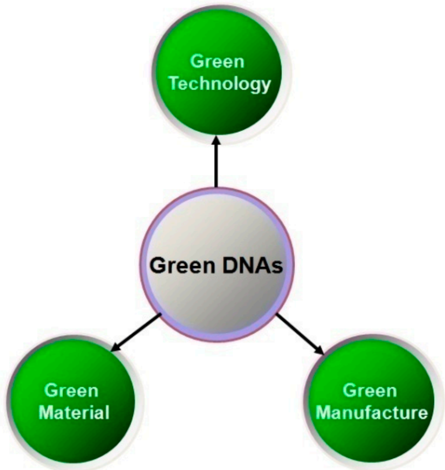

Figure 2. Three Green DNAs.

3.3.1. Green Technology

All relevant green energy and energy-saving technologies belong to the category of green technology, including solar power, wind power, hydropower generation, etc. These green technologies are the easiest for showing the effectiveness of green products. Designers are advised to prioritize design considerations from this green element when designing eco-friendly products.

3.3.2. Green Material

The eco-friendly 4R (Reduction, Reuse, Recycling, Regeneration) concept advocated by government agencies and private environmental groups is the most basic definition of green material properties. The newest green material technology has developed a type of biodegradable materials that are extracted from plant fibers. Therefore, when such items are discarded into the outside environment, they will be decomposed by microorganisms under certain temperature and humidity conditions, and will not cause harm to the environment. For example, polylactide (PLA) is one such material, which has been widely applied in the design of our daily necessities. In the future, designers are advised to prioritize the usage of biodegradable materials when looking for materials suitable for eco-friendly products.

3.3.3. Green Manufacture

For the sake of aesthetic appeal, products will be painted, plated, and printed to enhance the aesthetic appearance. Most of these post-processing procedures use organic solvents and produce harmful toxic substances. If these processes are not handled well, they will often cause environmental pollution and damage. Therefore, if designers can try not to apply these manufacturing processes in beautifying and decorating products, it would greatly reduce the environmental impact of their work.

However, these three Green DNAs do not just represent the meanings of "Green", they represent the concept of a Green database. Different industries will have various green technologies, green materials, and green manufacturing processes that can be applied. Details of these must be collected and studied by designers to build up their company's specific green database, which can then be applied when designing green products in the future.

3.4. Innovative Green Design Method

When facing a green product design, general designers often cannot grasp the design points or even know where to start. In the processes of the preliminary analysis of a product and conversion into a green product, if the three Green DNAs mentioned above—"green technology", "green material", and "green manufacture"—can be integrated into the design thinking of the extension method (Figure 3), then designers can easily grasp the design points and further develop innovative green products. The integration of both will obtain the complementary effects of the design. Therefore, a green extension method is proposed for practical green product design based on the extension theory and the three Green DNA concepts proposed in this study. The proposed innovative green design method adds the three Green DNA concepts to the analysis process of the extension method. When analyzing and transforming the new product matter–element models, the designers can import the three Green DNAs into the innovative concepts of the products to develop green products.

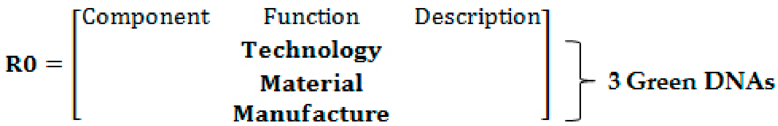

Figure 3. The design thinking of the green extension method.

The procedures of the proposed method are shown in Figure 4.

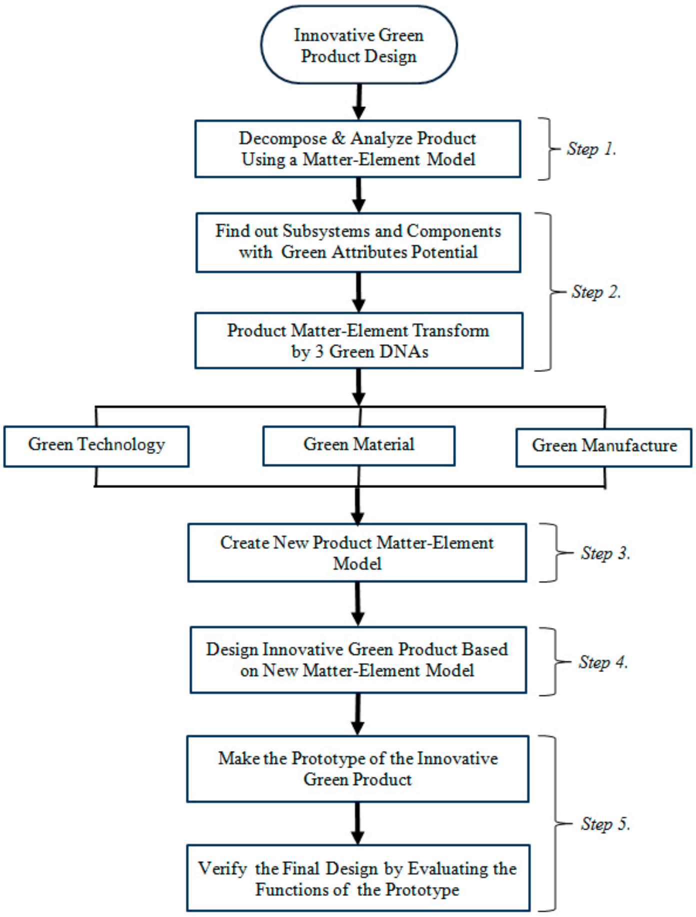

Figure 4. The procedures of the innovative green design method integrated with the extension method and three Green DNAs.

Step 1. Decompose and analyze the product using the matter–element model.

The product is decomposed and analyzed from the system and subsystem to the components in order to obtain complete mechanical and functional information.

Step 2. Find subsystems or components with innovative green values and opportunities.

The three Green DNAs are applied to examine the components and technology of the analysis system, which can introduce the concepts of green technology, green material, and green manufacture. This is done to apply different ways of working to achieve the eco-design goals.

Step 3. Apply the matter–element transformation to establish a new matter–element model.

After determining the target subsystems or components to be innovated or improved upon, a new product architecture is developed with the matter–element transformation. This can create new operational functions or methods for the products, even an innovative green design concept that is completely different from the existing products.

Step 4. Introduce a new matter–element model into practical product design.

Perform practical product design with a new matter–element model that incorporates green DNAs. The design points will focus on the integration of industrial design, mechanical design, and product functions.

Step 5. Make a product prototype to validate the green design concepts.

Finally, a product prototype is made based on the practical design, and this is used to verify the feasibility and effectiveness of the proposed innovative green product design.

Furthermore, this innovative green design method can not only drive designers to consider the three Green DNAs, but also can further assist them in reconstructing an innovative green product using the decomposing and recomposing process of the extension method. The process can facilitate the construction of the green modulars and improve product disassembly, thus raising the value added by product recycling. This is the main innovation of this method, which can help the final designed green product obtain the maximum sustainable benefits and achieve a win–win situation for the environment, consumers, and companies.

4. A Case Study

To prove the application of the proposed green design method, a practical product design case of an academia–industry cooperation project is illustrated, as follows:

4.1. Green Air Purifier Design

The company of the academia–industry cooperation is JJS Inc, which manufactures TTA nanomaterials. The company's main business is to promote and market TTA materials. TTA itself is an antibacterial and antiviral green material with the properties of being colorless and odorless. The easiest way to use it is to spray it directly onto the surface of an object to form a protective film that acts as an antibacterial and antiviral shield. The antibacterial and antiviral functions of TTA materials have been approved and certified by the FDA-Microbac laboratory in the USA. After discussing with JJS's engineers, we suggested that the characteristics of the TTA materials could be used to design and develop medical air purifiers. The preliminary definition of the TTA air purifier's functional specifications and features are as follows:

1. Antibacterial and antiviral function
2. Filter PM2.5 and formaldehyde organic substances
3. Show and warn about PM2.5 air quality
4. Air purification efficiency up to 200 CADR
5. Noise is less than 50 decibels
6. Filter replacement reminder
7. Easy to operate interface.

4.2. The Basic Matter–Element Model of the Air Purifier

In order to realize the design concept of this green TTA air purifier, this study uses the proposed green extension method to analyze and decompose the product and find a system or component that can introduce innovative green features. According to the commercially available air purifiers and the preliminary product specifications, we have constructed the basic matter element model of the general air purifier according to the extension method, as shown in Figure 5.

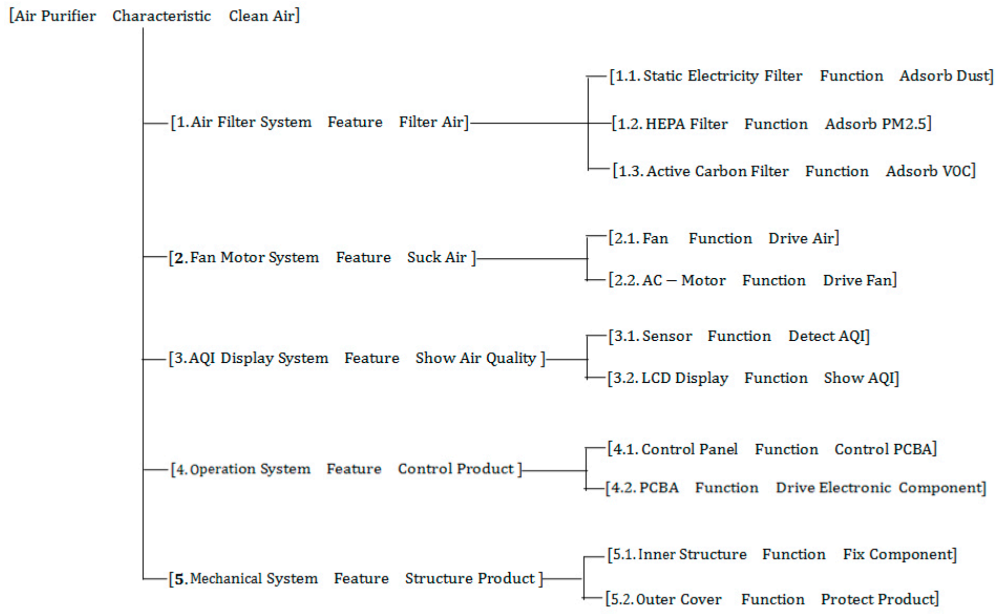

Figure 5. The basic matter–element model of the general air purifier.

4.3. The Transformation of the Matter–Element Model of the Air Purifier

In Figure 5, we found that the relevant components in the air filtration system, fan motor system, detecting and warning system (AQI system), and mechanical system have the opportunity to incorporate related innovative green features. This study further uses the transformation principle of the matter–element model of the green extension method to transform the new green system or green components to achieve the purpose of innovative green product design. The transformation of the matter–element model of the related components in the above four subsystems is explained below:

4.3.1. The Transformation of the Matter–Element Model of the Air Purifier System

A traditional air purifier is generally equipped with electrostatic filters, HEPA filters, and activated carbon filters to filter out air pollution, including PM2.5 and formaldehyde organic substances. In general, such a design does not effectively remove bacteria and viruses. The TTA air purifier is thus very different from the commercially available products, as the TTA has antibacterial and antiviral effects, and including this is also the most challenging part for this TTA air purifier design. Therefore, we hope to apply the matter–element model transformation principle of the green extension method to design the TTA filter as a green module. Because TTA is a liquid, it must be sprayed on the surface of an object to be effective. TTA can thus be sprayed on the air filter to kill bacteria and viruses when the air touches it in order to achieve the antibacterial and antiviral effects. Therefore, the TTA filter must be designed to be very small in volume but very large in surface area. At the same time, if we can consider the usage of green materials in the TTA filter, it will be beneficial for green innovation. For the design of the TTA filter, the principle of the addition transformation in the green extension method is adopted. We try to combine the TTA eco-friendly antibacterial materials with air filters. Consider the new TTA air filter design (TR0) from the TTA material properties (R0), as well as the air filter type and green material selection (R1). The overall design thinking process is as follows:

$$\mathbf{R0} = \begin{bmatrix} \text{TTA} & \text{Function} & \text{Antibacterial} \\ & \text{Form} & \text{Liquid} \\ & \text{Material} & \text{TiO}_2 + \text{Ag}^+ \end{bmatrix} \tag{15}$$

$$\mathbf{R1} = \begin{bmatrix} \text{Filter} & \text{Function} & \text{Clean Air} \\ & \text{Form} & \text{Hexagon Beehive} \\ & \text{Material} & \text{Al} \end{bmatrix} \quad (16)$$

$$\mathbf{TR0} = \mathbf{R0} \oplus \mathbf{R1} = \begin{bmatrix} \text{1.4.TTA Filter} & \text{Function} & \text{Clean Air with Antibacteria} \\ & \text{Form} & \text{Hexagon Beehive with Sprayed TTA} \\ & \text{Material} & \text{Al} + \text{TiO}_2 + \text{Ag}^+ \end{bmatrix} \quad (17)$$

Finally, based on the above design thinking, a hexagonal honeycomb TTA antibacterial air filter was proposed. The hexagonal honeycomb shape has characteristics such as the best structural strength and the largest surface area in the same volume, and it can be sprayed with the TTA materials for optimal antibacterial function. The material chosen is aluminum metal with light, strong, and recyclable attributes. It combines with the TTA to create a truly eco-friendly TTA air filter.

4.3.2. The Transformation of the Matter–Element Model of the Fan Motor System

The fan motor system of a general air purifier uses a high-voltage AC electric motor, which consumes a large amount of energy. If it can use a DC inverter motor, it would greatly reduce the energy consumption. At the same time, if the smart mode can be introduced on the control interface instead of the traditional manual control interface, it could also reduce more energy consumption during the use of the air purifier. The design thinking adopts the addition of the transformation principle in the green extension method. The entire deduction processes are as follows:

$$\mathbf{R2} = \begin{bmatrix} \text{2.2. AC} - \text{Motor} & \text{Function} & \text{Drive Fan} \\ & \text{Power} & \text{AC} - \text{Power} \\ & \text{Energy Consumption} & \text{High} \end{bmatrix} \quad (18)$$

$$\mathbf{TR2} = \begin{bmatrix} \text{2.3.DC} - \text{Motor} & \text{Function} & \text{Drive Fan} \\ & \text{Power} & \text{DC} - \text{Power} \\ & \text{Energy Consumption} & \text{Low} \end{bmatrix} \quad (19)$$

$$\mathbf{R3} = \begin{bmatrix} \text{Manu Operation} & \text{Function} & \text{Control Motor} \\ & \text{Power Frequecy} & \text{Fixed} \\ & \text{Energy Consumption} & \text{High} \end{bmatrix} \quad (20)$$

$$\mathbf{TR3} = \begin{bmatrix} \text{Auto} - \text{ Operation} & \text{Function} & \text{Auto} - \text{Control Motor} \\ & \text{Power Frequecy} & \text{Random} \\ & \text{Energy Consumption} & \text{Low} \end{bmatrix} \quad (21)$$

$$\mathbf{R4} = \begin{bmatrix} \text{3.1.Sensor} & \text{Function} & \text{Detect Air Quality} \\ & \text{Pollution} & \text{PM2.5 \& VOC} \end{bmatrix} \quad (22)$$

$$\mathbf{TR4} = \mathbf{TR2} + \mathbf{TR3} + \mathbf{R4} = \begin{matrix} \text{6.Smart System} & \text{Function} & \begin{matrix}\text{Drive Fan \& Autocontrol Motor} \\ \text{Speed by Sensor Detecting}\end{matrix} \\ & \text{Driver} & \text{Sensor} \\ & \text{Power /Frequency} & \text{DC} - \text{Power/Random} \\ & \text{Energy Consumption} & \text{Lowest} \end{matrix} \quad (23)$$

The final design thinking is to develop a smart control system (TR4) that can automatically adjust the speed (TR2) of the variable-frequency DC motor according to the air quality monitored by the sensor (R4) (PM2.5 and the concentration of formaldehyde). For example, if PM2.5 is detected or the formaldehyde concentration is too high, the system will automatically increase the fan motor speed to quickly filter out the source of the pollution. Conversely, the fan motor speed is automatically reduced to achieve the best air cleaning effect. At the same time, it can also achieve the effect of energy saving, thereby killing two birds with one stone.

4.3.3. The Transformation of the Matter–Element Model of the Detecting and Warning System

Traditional air purifiers mostly use an LCD Display to reveal the air quality conditions, which consumes a lot of energy. Therefore, the replacement principle of the green extension method is adopted by replacing the LCD Display with an LED Display, as this will reduce the energy consumption. The processes of design thinking are as follows:

$$\mathbf{R}3 = \begin{bmatrix} \text{3.2.LCD Display} & \text{Function} & \text{Show Air Quality} \\ & \text{Power} & \text{High Voltage} \\ & \text{Energy Consumption} & \text{High} \end{bmatrix} \tag{24}$$

$$\mathbf{TR}3 = \begin{bmatrix} \text{3.3.LED Display} & \text{Function} & \text{Show Air Quality} \\ & \text{Power} & \text{Low Voltage} \\ & \text{Energy Consumption} & \text{Low} \end{bmatrix} \tag{25}$$

4.3.4. The Transformation of the Matter–Element Model of the Appearance Cover System

The appearance covers of general household appliances are mostly made of acrylonitrile butadiene styrene (ABS) material. ABS is a petrochemical plastic material that is less friendly to the environment. If we can replace the ABS with the biodegradable material PLA by using the replacement principle of the green extension method, then the environmental impact can be greatly reduced. At the same time, in order to achieve the purpose of reducing the usage of raw materials, the thickness of the outer cover is changed from 3 to 2.5 mm without compromising strength or safety. The overall shell weight has also been reduced by 16.67%. This contributes to the reduction of raw materials. After the injection molding of the general plastic covers, for the sake of aesthetics, post-processing manufacturing for the surface coating and printing will be carried out. Most of the painting and printing inks used contain volatile organic solvents. These volatile organic substances are also very contaminating to the environment. The cover of this TTA air purifier will thus not be painted and printed. The overall design thinking processes are as follows:

$$\mathbf{R}4 = \begin{bmatrix} \text{5.2. Outer Cover} & \text{Function} & \text{Appearance \& Protection} \\ & \text{Material} & \text{ABS} \\ & \text{Manufacture} & \text{With Painting \& Printing} \\ & \text{Thickness} & \text{3 mm} \end{bmatrix} \tag{26}$$

$$\mathbf{TR}4 = \begin{bmatrix} \text{5.3.Outer Cover} & \text{Function} & \text{Appearance \& Protection} \\ & \text{Material} & \text{PLA} \\ & \text{Manufacture} & \text{Without Painting \& Printing} \\ & \text{Thickness} & \text{2.5 mm} \end{bmatrix} \tag{27}$$

4.3.5. The New Matter–Element Model of the TTA Air Purifier

A traditional air purifier does not look like a green product. However, through the above proposed green extension method, we successfully introduced the Green DNAs into the air filter system, fan motor system, detecting and warning system, and the appearance cover system. These transformations make this TTA air purifier have the concept of innovative green design. In addition, some green modulars are developed, including the fan motor system, AQI display system, TTA filter subsystem, and smart control system. The establishment of these green modulars also facilitates product disassembly. These new green features of the proposed product help reduce the environmental impact. The transformed matter–element model of the TTA air purifier is as shown in Figure 6.

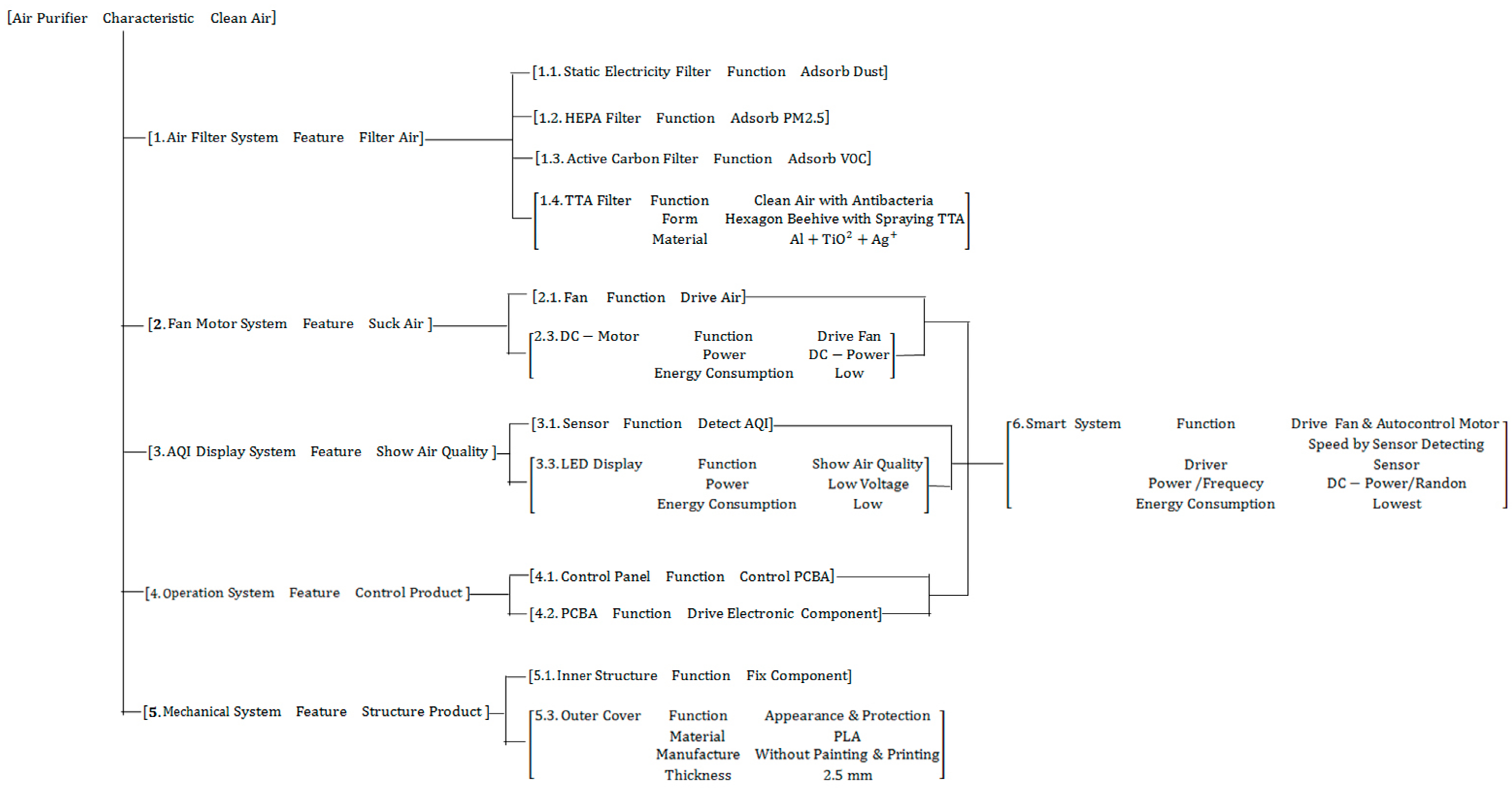

Figure 6. The new matter–element model of the TTA air purifier after transformations.

4.4. The Practical Product Design of the TTA Air Purifier

Based on the new matter–element model of the TTA air purifier, this study has designed a medical TTA air purifier using the processes of new product development (NPD) (Figures 7 and 8). The NPD processes embrace idea sketching, industrial design, mechanical design, mockup making, 3D CAD modeling, and prototype making. The design features of this innovative medical TTA air purifier include: 1. Green TTA filter; 2. DC inverter motor; 3. Automatic AQI display and warning; 4. Smart mode design; 5. PLA biodegradable material. These characteristics have significant effects on green product design. At the same time, and using the final design files of 3D CAD, a 3D printer is used to make the prototype of the TTA air purifier (Figure 9). It can be used to verify the functional quality of this proposed green design.

Figure 7. The final design of the medical TTA air purifier.

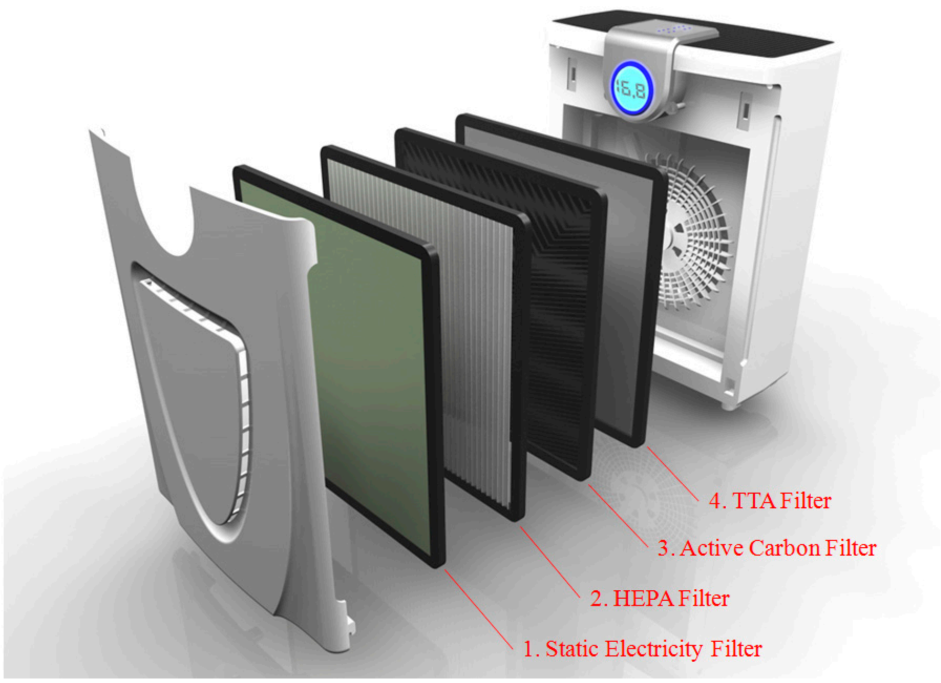

Figure 8. The structure of the medical TTA air purifier.

Figure 9. The prototype of the medical TTA air purifier.

5. Results and Discussions

5.1. The Evaluation of Product Functions and Green Features

In order to verify the functions of the newly designed TTA air purifier, the prototype was sent to Société Générale de Surveillance (SGS) for third party certification and functional testing. The testing items included the removal efficiency rate for PM2.5, organic volatile formaldehyde molecules, and the most important bacterial elements. The final test results show that this innovative TTA air purifier had an elimination ratio of 99.9% for PM2.5, formaldehyde molecules, and bacteria, as shown in Table 1 [64]. This effect is much better than that seen with general commercial air purifiers.

Table 1. Test results of SGS (Société Générale de Surveillance).

Test Item	Unit	Control Test	Experiment Test	Elimination Ratio (%)
Fine Suspended Particulates (PM2.5)	ug/m^3	1140	<1	>99.9
Total Bacteria Counts	CFU/m^3	4005	<6	>99.9
Formaldehyde	ppm	0.857	<0.001	>99.9

In addition to the function verification of air filtration by SGS, this prototype was also tested for other related functions (Table 2). The tests showed that the air purification rate reaches 300 CADR, higher than the general specification of 200 CADR, and the overall machine noise is lower than 40 decibels, which is also better than the general 50 decibels. In the smart mode design, PM2.5-detected data is automatically displayed along with AQI warnings using differently colored LEDs. The test of the interface design showed that the three-phase timing (1/4/8 h) and three air volume mode (low/medium/high) functions also work normally. Finally, regarding green design verification, since the prototype adopts an LED display, DC inverter motor, and intelligent electric control mode, the actual power consumption is 60 watt/h, which is much better than the ordinary 150 watt/h. The case cover is made of PLA biodegradable material. The actual measured thickness is 2.5 mm, which is thinner than the normal 3 mm. The overall case material can be reduced by 500 g per set. In terms of filter consumption, the TTA filter can be used permanently and does not need to be replaced. When it is dirty, it can be reused after washing and drying. In addition to reducing filter consumption, it can also help consumers save approximately 120 USD per year (30 USD/season × 4 seasons). From the testing results, we have proven that this innovative TTA air purifier has indeed reached the expected design target. This can be regarded as a successful design and development project for a green product. In addition to the green design concept, this innovative air purifier also makes a significant contribution to epidemic prevention in medicine due to the characteristics of its antibacterial and antiviral function. In terms of green modular design, four green modulars are created, including a fan motor system, AQI display system, TTA filter subsystem, and smart control system. Furthermore, these green modulars provide a better product structure for the planning of product disassembly and recycling.

Table 2. Test results of the related verification.

Items	Test Results (Specifications)	Verification
Rate of air clean	Over 300 CADR (200 CADR)	PASS
Clean function	1. PM 2.5 elimination ratio: >99.9% 2. Bacteria elimination ratio: >99.9% 3. Formaldehyde elimination ratio: >99.9%	PASS (SGS Reports)
Detecting function	Auto detect PM2.5 and display the data	PASS
Warming function	Auto warn PM2.5: show AQI by different color	PASS
Air volume	Three modes: low/medium/high	PASS
Timer function	Three modes: 1 h/4 h/8 h	PASS
Noise	Under 40 decibel (50 decibel)	PASS
Power consumption	Under 65 watt/h (150 watt/h)	PASS
Outer cover thickness	2.5 mm (3 mm)	PASS

On the other hand, from the perspective of green economics [65], for producers, in order to introduce relevant green design concepts in the early stage, the production cost of an air purifier may be more than 100 USD, but the selling price can be increased by 200 USD. The overall profits and returns have thus increased. For consumers, purchasing a green air purifier may cost an additional 200 USD, but in the long term, it helps consumers reduce their electricity bills to cover the purchase cost of this extra expenditure (1 kWh = 0.2 USD). Meanwhile, it can also reduce the generation of carbon emissions (1 kWh = 0.625 kg/CO_2). Assuming that this green air purifier is turned on for 8 h a day, it is estimated that carbon emissions can be reduced by 164.25 kg in a year (0.09 (kWh) × 8 (h) × 365 (day) × 0.625 (kg/CO_2) = 164.25 kg). Ten thousand units can therefore reduce carbon emissions by 1642.5 metric tons. In the long term, such a green economy concept can greatly reduce the impact on the environment. This premise is based on the idea that producers and consumers have a green awareness of each other, so that the concept of a green economy can be fully formed. Finally, a win–win situation for producers, consumers, and the environment can be achieved.

5.2. The Evaluation of the Green Design Method

This green design method was provided to the designers of a lighting manufacturer to assess the feasibility and effectiveness of the proposed method. These lighting designers had previously utilized the Quality Function Deployment (QFD) method [66] to design a desk lamp. Similarly, these designers were asked to apply the proposed design method in designing a desk lamp. An interview was conducted after they had finished, and feedback was obtained from these designers. Firstly, with regard to the advantages, they think that both this innovative green design method and QFD use the concept and process of decomposition and composition, and both can help designers complete a product design. However, if the design target is for green products, the approach we provided is more useful and powerful. This is because the proposed method can clearly guide the designers to analyze the potentials of incorporating green features from three Green DNAs in the early stage of the product design, instead of going in the wrong direction at the beginning, which can result in the final designed product not having any green attributes. Meanwhile, they also mentioned that this method does not have many calculation processes, unlike QFD, and thus is more efficient. The new approach can provide designers with complete and detailed steps of decomposing and recomposing products. This will be helpful for developing green modular and product disassembly designs. On the other hand, with regard to the shortcomings of the proposed method, the designers indicated that although this method is better than QFD in feasibility and efficiency, both QFD and this method cannot offer detailed design solutions. For example, LEDs are used to design a green desk lamp. Due to thermal issues, heatsinks need to be adopted to assist in heat dissipation. In this process, the proposed method can help decompose and reconstruct the green modular by combining LEDs with heatsinks, but it cannot assist designers in generating the detailed design solutions needed for the optimal structure of combining LEDs with heatsinks. This is the main drawback that designers gave us in their feedback. This response will encourage us to improve the proposed method with regard to idea generation. The comparison between QFD and the proposed green design method is shown in Table 3. Basically, from the case study and feedback from the designers, we know that this innovative green design method has certain strengths in terms of feasibility and efficiency, but it still needs to be strengthened in generating detailed design solutions.

Table 3. The comparison between Quality Function Deployment (QFD) and the proposed method.

Item	Feasibility	Efficiency	Design Solution Generation
Proposed Method	○	○	X
QFD Method	○	△	X

Remark: ○ = Excellent, △ = Medium, X = Poor.

6. Conclusions

Nowadays, most companies are faced with the challenge of creating products with less environmental impact in order to develop a more sustainable society. Green design is one of the most important ways to cope with this challenge. A green design method is defined as a practical tool to reduce the environmental impact of a product at the early design stage. The traditional design method and processes place too much emphasis on the functional design and optimizing module design, ignoring which systems and parts have the opportunity to introduce related green concepts, such as green materials, green energy saving, and green processes at the beginning of the design, and thus missing the opportunity to be a good green product. The proposed green design method is developed based on the extension method and the three Green DNAs. It has specific decomposing rules and transforming approaches, which can assist designers in solving green design problems. Clear operating principles and detailed steps are also provided for green product design in practical applications. In addition to the concept of Green DNAs, this innovative green design method provides designers with the opportunity to develop green modulars and to consider product disassembly during the process of decomposing and recomposing analysis. From the above practical case study, we can find that this innovative method is indeed feasible and effective. We thus hope that this innovative green design method may contribute to the development and design of green products for companies. At present, this innovative method still has a major problem in that it cannot assist designers in generating detailed design solutions. In future works, we will thus aim to improve the process of idea generation by combining the extension method and TRIZ theory to develop a novel green design method. This is important, as good products must be green products in the future, when the real power of green design can be seen throughout the world.

Funding: This study was supported in part by the Ministry of Science and Technology of Taiwan under grant MOST 107-2745-8-029-001.

Conflicts of Interest: The author declares no conflict of interest.

References

1. Papanek, V.; Lazarus, E.L. *Design for the Real World: Human Ecology and Social Change, 2nd ed*; Academy Chicago Publishers: Chicago, IL, USA, 2005.
2. Kurk, F.; Eagan, P. The value of adding design-for-the-environment to pollution prevention assistance options. *J. Clean. Prod.* **2008**, *16*, 722–726. [CrossRef]
3. Gheorghe, R.; Ishii, K. Eco-design value alignment—Keys to success. In Proceedings of the ASME International Mechanical Engineering Congress and Exposition, Seattle, WA, USA, 11–15 November 2007; Volume15, pp. 267–277.
4. Tulacz, G.; Traynor, M. The top 100 green design firms. *Eng. News Rec.* **2008**, *260*, 116–118.
5. Zhu, Q.; Sarkis, J. The moderating effects of institutional pressures on emergent green supply chain practices and performance. *Int. J. Prod. Res.* **2007**, *45*, 4333–4355. [CrossRef]
6. Mahmoud-Jouini, S.B.; Midler, C.; Silberzahn, P. Contributions of design thinking to project management in an innovation context. *Proj. Manag. J.* **2016**, *47*, 144–156. [CrossRef]
7. Brown, T. Design thinking. *Harv. Bus. Rev.* **2008**, *86*, 84–92.
8. Brown, T.; Katz, B. Change by design. *J. Prod. Innov. Manag.* **2011**, *28*, 381–383. [CrossRef]
9. Geissdoerfer, M.; Bocken, N.M.; Hultink, E.J. Design thinking to enhance the sustainable business modelling process—A workshop based on a value mapping process. *J. Clean. Prod.* **2016**, *135*, 1218–1232. [CrossRef]
10. Shapira, H.; Ketchie, A.; Nehe, M. The integration of design thinking and strategic sustainable development. *J. Clean. Prod.* **2017**, *140*, 277–287. [CrossRef]
11. Cai, W. The extension set and non-compatible problem. *Sci. Explor.* **1983**, *3*, 83. (In Chinese)
12. Gonzalez-Benito, J.; Gonzalez-Benito, O. Operations management practices linked to the adoption of ISO 14001: An empirical analysis of spanish manufacturers. *Int. J. Prod. Econ.* **2008**, *113*, 60–73. [CrossRef]
13. Murillo-Luna, J.L.; Garcés-Ayerbe, C.; Rivera-Torres, P. Why do patterns of environmental response differ? A stakeholders' pressure approach. *Strateg. Manag. J.* **2008**, *29*, 1225–1240. [CrossRef]
14. Unruh, G.; Ettenson, R. Growing green. *Harv. Bus. Rev.* **2010**, *88*, 94–100.
15. Rehfeld, K.M.; Rennings, K.; Ziegler, A. Integrated product policy and environmental product innovations: An empirical analysis. *Ecol. Econ.* **2007**, *61*, 91–100. [CrossRef]
16. Albino, V.; Balice, A.; Dangelico, R.M. Environmental strategies and green product development: An overview on sustainability-driven companies. *Bus. Strategy Environ.* **2009**, *18*, 83–96. [CrossRef]
17. Chung, Y.; Tsai, C. The effect of green design activities on new product strategies and performance: An empirical study among high-tech companies. *Int. J. Manag.* **2007**, *24*, 276–288.
18. Berchicci, L.; Bodewes, W. Bridging environmental issues with new product development. *Bus. Strategy Environ.* **2005**, *14*, 272–285. [CrossRef]
19. Miller, J.; Szekely, F. What is green? *Eur. Manag. J.* **1995**, *13*, 322–333. [CrossRef]
20. McDonagh, P.; Prothero, A. *Green Management: A Reader*; The Dryden Press, Harcourt Brace & Company Limited: London, UK, 1996.
21. Roy, R.; Wield, D.; Gardiner, J.P.; Potter, S. *Innovative Product Development*; The Open University: Milton Keynes, UK, 1996.
22. Chen, C. Design for the environment: A quality-based model for green product development. *Manag. Sci.* **2001**, *47*, 250–263. [CrossRef]
23. Commission of the European Communities, Green Paper on Integrated Product Policy. 2001. Available online: http://eur-lex.europa.eu/LexUriServ/site/en/com/2001/com2001_0068en01.pdf (accessed on 10 November 2019).
24. Dangelico, R.M.; Pontrandolfo, P. From green product definitions and classifications to the Green Option Matrix. *J. Clean. Product.* **2010**, *18*, 1608–1628. [CrossRef]
25. Pujari, D. Eco-innovation and new product development: Understanding the influences on market performance. *Technovation* **2006**, *26*, 76–85. [CrossRef]

26. Baumann, H.; Boons, F.; Bragd, A. Mapping the green product development field: Engineering, policy and business perspectives. *J. Clean. Prod.* **2002**, *10*, 409–425. [CrossRef]
27. Ottman, J.A.; Stafford, E.R.; Hartman, C.L. Green marketing myopia. *Environment* **2006**, *48*, 22–36.
28. Shrivastava, P. Environmental technologies and competitive advantage. *Strateg. Manag. J.* **1995**, *16*, 183–200. [CrossRef]
29. Kaebernick, H.; Soriano, V. An Approach to Simplified Environmental Assessment by Classification of Products. In Proceedings of the Seventh CIRP International Conference on Life Cycle Engineering, Tokyo, Japan, 27–29 November 2000.
30. Dewberry, E.; Goggin, P. Spaceship Ecodesign. *Co-Design* **1996**, *5/6*, 12–17.
31. Calza, F.; Parmentola, A.; Tutore, I. Types of green innovations: Ways of implementation in a non-green industry. *Sustainability* **2017**, *9*, 1301. [CrossRef]
32. Ferrer, J.B.; Negny, S.; Robles, G.C.; Le Lann, J.M. Eco-innovative design method for process engineering. *Comput. Chem. Eng.* **2012**, *45*, 137–151. [CrossRef]
33. Bocken, N.; Allwood, J.; Willey, A.; King, J. Development of an eco-ideation tool to identify stepwise greenhouse gas emissions reduction options for consumer goods. *J. Clean. Product.* **2011**, *19*, 1279–1287. [CrossRef]
34. Eastwood, M.D.; Haapala, K.R. A unit process model based methodology to assist product sustainability assessment during design for manufacturing. *J. Clean. Prod.* **2015**, *108*, 54–64. [CrossRef]
35. Livotov, P. Sustainable european collaboration in the field of knowledge-based innovation and inventive problem solving with TRIZ, 1866-4180. *J. Eur. Triz Assoc.* **2017**, 1–3.
36. Russo, D.; Serafini, M.; Rizzi, C. Is TRIZ an Ecodesign Method? In *Sustainable Design and Manufacturing 2016. SDM 2016. Smart Innovation, Systems and Technologies*; Setchi, R., Howlett, R., Liu, Y., Theobald, P., Eds.; Springer: Cham, Germany, 2016; Volume 52.
37. Mann, D. Systematic Sustainable Innovation, Sustainable Innovation 03: Creating sustainable products, services and product-service-system, Towards Sustainable Product Design. In Proceedings of the 8th International Conference, Stockholm, Sweden, 27–28 October 2003.
38. Wu, Y.H.; Ho, C.C. Integration of green quality function deployment and fuzzy theory: A case study on green mobile phone design. *J. Clean. Prod.* **2015**, *108*, 271–280. [CrossRef]
39. Thankia, S.; Govindanb, K.; Thakkarc, J. An investigation on lean-green implementation practices in Indian SMEs using analytical hierarchy process (AHP) approach. *J. Clean. Prod.* **2016**, *135*, 284–298. [CrossRef]
40. Chen, J.L.; Liu, C.C. An eco-innovative design approach incorporating the TRIZ method without contradiction analysis. *J. Sustain. Prod. Des.* **2001**, *1*, 263–272. [CrossRef]
41. Chen, J.L.; Liu, C.C. Green innovation design of products by TRIZ inventive principles and green evolution rules. In Proceedings of the 2002 International CIRP Design Seminar, Hong Kong, 16–18 May 2002.
42. Chang, H.T.; Chen, J.L. An Eco-Innovative Design Method Based on Design around Approach. In Proceedings of the Third International Symposium on Environmentally Conscious Design and Inverse Manufacturing, Ecodesign03, Tokyo, Japan, 8–11 December 2003.
43. Altshuller, G.S. *40 Principles: TRIZ Keys to Technical Innovation*; Shulyak, L., Rodman, S., Eds.; Technical Innovation Center: Worcester, MA, USA, 1997.
44. Altshuller, G.S. *Creativity as an Exact Science:The Theory of the Solution Inventive Problems*; Gordon and Breach Science Publishing: New York, NY, USA, 1984.
45. Ishii, K. Product Modularity: A Key Concept in Life-Cycle Design. In *Second Annual Symposium on Frontiers of Engineering*; National Academy Press: Washington, DC, USA, 1997; pp. 17–24.
46. Huang, H.H.; Liu, Z.F.; Wang, S.W.; Liu, G.F.; Guo, W.X. Research on methodology of modular design for recycling. *Trans. Chin. Soc. Agric. Mach.* **2006**, *37*, 144–149.
47. Gu, P.; Sosale, S. Product modularization for life cycle engineering. *Robot. Comput. Integr. Manuf.* **1999**, *15*, 387–401. [CrossRef]
48. Umeda, Y.; Fukushige, S.; Tonoike, K.; Kondoh, S. Product modularity for life cycle design. *CIRP Ann. Manuf. Technol.* **2008**, *57*, 13–16. [CrossRef]
49. Tseng, H.E.; Chang, C.C.; Li, J.D. Modular design to support green lifecycle engineering. *Expert Syst. Appl.* **2008**, *34*, 2524–2537. [CrossRef]
50. Smith, S.; Yen, C.C. Green product design through product modularization using atomic theory. *Robot. Comput. Integr. Manuf.* **2010**, *26*, 790–798. [CrossRef]

51. Yi, J.; Ji, B.; Guan, Y.; Dong, J.; Li, C. Research on evaluation methodologies of product life cycle engineering design (LCED) and development of its tools International. *J. Comput. Integr. Manuf.* **2008**, *21*, 923–942.
52. Pnueli, Y.; Zussman, E. Evaluating the end-of-life value of a product and improving it by redesign. *Int. J. Prod. Res.* **1997**, *35*, 921–942. [CrossRef]
53. Seo, K.; Park, J.; Jang, D.; Wallace, D. Approximate estimation of the product life cycle cost using artificial neural networks in conceptual design. *Int. J. Adv. Manuf. Technol.* **2002**, *19*, 461–471. [CrossRef]
54. Xanthopoulos, A.; Iakovou, E. On the optimal design of the disassembly and recovery processes. *Waste Manag.* **2009**, *29*, 1702–1711. [CrossRef] [PubMed]
55. Aguinaga, I.; Borro, D.; Matey, L. Parallel RRT-based path planning for selective disassembly planning. *Int. J. Adv. Manuf. Technol.* **2008**, *36*, 1221–1233. [CrossRef]
56. Kara, S.; Pornprasitpol, P.; Kaebernick, H. Selective disassembly sequencing: A methodology for the disassembly of end-of-life products. *Ann. CIRP* **2006**, *55*, 37–40. [CrossRef]
57. Shyamsundar, N.; Gadh, R. Selective disassembly of virtual prototypes, Proceedings of the IEEE International Conference on Systems, Man and Cybernetics. *Inf. Intell. Syst.* **1996**, *4*, 3159–3164.
58. Cai, W. *Matter-Element Analysis*; Guangdong Higher Education Publishers: Guangzhou, China, 1987. (In Chinese)
59. Cai, W. *Matter-Element Models and Their Application*; Science and Technology Documentation Publishers: Beijing, China, 1994. (In Chinese)
60. Cai, W. Introduction of Extenics. *Syst. Eng. Theory Pract.* **1998**, *18*, 76. (In Chinese)
61. Cai, W.; Yang, C.; Lin, W. *Methods of Extension Engineering*; Science Press: Beijing, China, 1997. (In Chinese)
62. Wang, W.L.; Zhao, Y.W. Research extension decision of mechanical intelligent CAD system. *Syst. Eng. Theory Pract.* **1998**, *18*, 114–117. (In Chinese)
63. Ye, J. Application of extension theory in misfire fault diagnosis of gasoline engines. *Expert Syst. Appl.* **2009**, *36*, 1217–1221. [CrossRef]
64. SGS Report Query Website. 2019. Available online: https://twap.sgs.com/sgssip/Report_Query.aspx (accessed on 20 December 2019).
65. Kennet, M.; Heinemann, V. Green Economics: Setting the scene. Aims, context, and philosophical underpinning of the distinctive new solutions offered by Green Economics. *J. Green Econ.* **2006**, *1*, 68–102. [CrossRef]
66. Akao, Y. *Quality Function Deployment: Integrating Customer Requirements into Product Design*; Productivity Press: Cambridge, MA, USA, 1990.