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Green Product Design Based on the BioTRIZ Multi-Contradiction Resolution Method

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Abstract: The impacts on the environment of many commercial products have not been fully considered in past years. For the sustainable development of Earth's resources, future product design should move towards not only innovation, but also fundamentally in the green direction. Currently, the BioTRIZ method may provide a satisfactory solution for a single contradiction of green product design. However, if there are multiple contradictions existing due to multiple operational fields, difficulty in implementing design aspects may be posed. For this reason, this paper develops a BioTRIZ multi-contradiction resolution method targeting a green product design, which can find the crucial contradictions and thus achieve the necessary invention principles (IP). By summarizing the green factors and further dividing operational fields, the deduced matrix table becomes highly effective in the design. Accordingly, designers can be assisted to quickly find the operational fields under multiple contradictions. The effectiveness of the proposed method is verified using a product example of a window-cleaning robot design.

Keywords: BioTRIZ; multi-contradiction; green design; bionic

1. Introduction

The development of technology plays a crucial role in economic growth. However, it was usually focused on novelty and economic practicability in past decades, somehow ignoring the impact on the environment [1]. With the increasing sustainable trend around the world, the green design moved forward faster than before since the 1990s. Product design for sustainability thus became a hot research area [2]. Development of methods for what drives sustainability, innovation, and value in green design continues to move forward [3]. This implies that the social sustainability in design should demonstrate a more pragmatic direction [4]. On the other hand, based on the inspiration from biological nature, product design with biomimetics is involved in the green design process [5]. For instance, in the decision-making design stage, ant colony algorithms and genetic algorithms are useful in achieving an optimal allocation of resources and energy [6]. In order to study the drag reduction mechanism of a bionic ribbed subsoiler, a soil particle motion analysis model using discrete element analysis was established [7]. As above literatures, a green design on aspects of sustainability is involved in strategies for sustainable innovation with bionics. This concept inspires the proposed BioTRIZ multi-contradiction resolution method.

To enhance the design process, it is well known that TRIZ is a powerful tool that can effectively stimulate product creativity in many fields, including green design [8]. Accordingly, it is important to establish a correlation table between environmental efficiency elements and engineering parameters (EP) [9]. Currently, the combination of bionics and TRIZ has caused progress in green design. Chen [10]

used TRIZ to search for biological keywords with the Noun1–Noun2–Verb model so that system contradictions and related biological cases could be found and analyzed. Chen and Hung [11] proposed an eco-innovation design method combining bionics and TRIZ, and established the connection between biological cases of TRIZ and invention principles (IP) through keywords. Guo et al. [12] combined the TRIZ contradiction matrix with bionics to obtain IP through the TRIZ matrix. Therefore, the suitable bionic prototype was found to achieve a lightweight product design.

Although TRIZ with bionic applications has made progress in green design, Vincent [13] revealed that there would be obstacles to directly using it if TRIZ is derived from technical and non-living systems. Thus, based on the TRIZ contradiction matrix, Vincent created a biological solution matrix for design contradiction, known as BioTRIZ [14]. Bogatyrev [15] proposed BioTRIZ in an ecological design to restore the damaged ecosystem. Many cases have been widely applied. For example, the anti-erosion properties of valve cores could be effectively improved, and the sealing face on valve cores can be protected from wear [16]. In the process of contradiction resolution using BioTRIZ, the increasing complexity of design problems in industry may result in a large number of involved contradictions [17]. There are one-to-many characteristics of customer requirements and operational fields, such as “improving the disassembly of the product”, which is related to structure and space. The multi-contradiction problems may be resolved mainly from three aspects: the analysis of the complex product problem [18], the expression of the multi-contradiction problem-solving process [19], and the determination of key contradictions [20,21]. These methods can accelerate problem solving, but some unsolved contradictions may still remain.

The paper is structured as follows: Section 2 presents a brief review for the fundamentals of BioTRIZ and green factors. The proposed methodology based on BioTRIZ multi-contradiction resolution method for green product design is introduced in Section 3. In Section 4, the improved design of the window-cleaning robot verifies the feasibility and effectiveness of the proposed model. Finally, conclusions are made, and prospective work is suggested for future study.

2. Fundamentals of BioTRIZ and Green Factors

2.1. Principles of BioTRIZ

BioTRIZ originated from biological functions, and it is based on subdivision of the operational fields using biology-related EP. It divides 39 EPs of TRIZ into six operational fields, including substance, structure, space, time, energy, and information. Mann pioneered the concept of combining bionic cases with TRIZ [22,23]. He pointed out that some EPs in the original TRIZ matrix were not included in the bionic design. To achieve contradiction resolution, 28 NEPs (Matrix Parameters Relevant to Natural World Design Solutions, NEP) related to nature’s successful solutions were reported [24].

Based on the principle of rationality, a questionnaire survey was taken by 35 scholars using the BioTRIZ tool. In the first stage, the questionnaire established the correspondence between four NEPs and each operational field. Some cases and applications from BioTRIZ were used for analysis, as summarized in Table 1 [25–27]. The relationship between each NEP and the corresponding operational field was scored using a scale of 1–5, representing extreme non-correspondence, non-correspondence, general correspondence, correspondence, and extreme correspondence, respectively. Statistical analysis of the survey data was performed using the SPSS software for each NEP, and the corresponding operational field average value was calculated by using the mean function of SPSS, and the average is sorted in a descending order (1-5 scale). The operational fields with the highest scores were regarded as the corresponding operational fields. Finally, this formed “Durability/Robustness/Life” as a corresponding operational field for structure, “Noise” as a corresponding operational field for energy, “Duration of Action” as a corresponding operational field for time, and “Amount of Information (Memory)” as a corresponding operational field for information. It is concluded that the BioTRIZ operational fields are subdivided to 28 NEPs, as shown in Table 2.

Table 1. Case study analysis using Matrix Parameters Relevant to Natural World Design Solutions (NEPs) and operational fields.

NEP	Operational Field	Application Instance	References
Durability/Robustness/Life	Structure	A roof can be designed for hot climates to get free cooling through radiant coupling with the sky. The insulating roof stops the sun and convection from warming the thermal mass.	Craig S. et al. [25].
Noise	Energy	Compared with traditional internal combustion engines, electric vehicles have improved noise inside and outside the vehicle after changing the type of energy.	Mosquera et al. [26].
Duration of Action	Time	The automobile disc brake can be designed from bionic points to increase the abrasion resistance and reduce its natural frequency.	Chen et al. [27].
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Table 2. NEPs corresponding to BioTRIZ Fields.

Fields	NEP
Substance	Weight, Loss of Substance, Amount of Substance
Structure	Stability, Complexity, Durability/Robustness/Life
Space	Length, Area, Volume, Shape
Time	Speed, Productivity/Reproduction, Duration of Action
Energy	Force, Stress/Pressure, Strength, Temperature, Illumination Intensity/Brightness, Energy/Power, Function Efficiency, Noise
Information	Security/Protection/Vulnerability, Harmful Effects By System, Harmful Effects on System, Repairability/Healing, Adaptability, Ability to Detect/Precision, Amount of Information (Memory)

2.2. Solutions to Problems Using BioTRIZ

In this step, first, the green factors corresponding to the technical characteristics are found. Second, the NEP related to the technical characteristics with $\sqrt{\quad}$ as a mark is found. The deteriorated characteristics are filled in using the same steps. If there is no corresponding green factor in the deteriorated characteristics, the relevant NEP is directly found. Then, the importance value is given according to the strength of the correlation, i.e., strong correlation, medium correlation, and weak correlation values are 9, 3, and 1, respectively.

The degree of correlation R_j^+ between the number of green factors, m , needs to be improved. The j th NEP can be obtained from Equation (1), and the resulting degree of correlation R_j^- between the deteriorated parameters and the j th NEP can be obtained from Equation (2).

$$R_j^+ = \sum_{i=1}^m v_{ji} \times w_i, 0 \leq m \leq k \tag{1}$$

$$R_j^- = \sum_{i=1}^n v_{ji} \times w_i \times R_i^{num}, 0 \leq n \leq k \tag{2}$$

where m is the number of green characteristics to be improved, and n is the number of parameters that may be deteriorated by m green characteristics. k is the number of green factors. W_i is the importance of demand, and R_i^{num} is the number of which the i th parameter may be deteriorated by m green characteristics.

When the NEP importance scores in each operational field are cumulated, the importance score of each operational field can be achieved. According to the ranking of the scores, the operational

field O^+ that is most closely related to the improved m green factors can be found for the evaluation of deterioration.

2.3. Green Factors

Green design aims to reduce the environmental impact of the product [28]. Nevertheless, it should consider the realization of basic functions, such as service life, economy, quality, etc. [29]. In addition, the solutions of green design should be comprehensive in three major aspects, i.e., environment, technology, and economy; more details are shown in the following [30].

1. **Environment:** Masui [31] proposed 15 environmental VOCs (Voices of Customers) to solve most environmental problems for direct incorporation into product development. Some customer requirements in environmental VOCs can be summarized as green factors. For example, the item 5, “easy to process and assemble”, and the item 8, “easy to disassemble”, can be summarized as disassembly factors, and item 2 “less energy efficient” can be classified as an energy efficiency factor. A total of seven environmental factors were extracted from the environmental VOCs: Energy efficiency, material, disassembly, maintainability, durability, emission of harmful substances, and product disposal.
2. **Technology:** Darko [32] revealed that the development of new products should ensure the advanced nature of technology and consider the efficiency, quality, structural, service life, safety, and reliability. Therefore, technical factors should be included in the evaluation items [33]. According to the principle of non-repetitive extraction of factors, seven environmental factors, extracted as above, were excluded, and two technical factors, i.e., efficiency and reliability, were extracted from Sun’s study.
3. **Economics:** Dong [34] classified the economics into customer cost, social cost, and enterprise cost in the product life cycle assessment.

The green factors are summarized from the above three aspects, as shown in Figure 1.

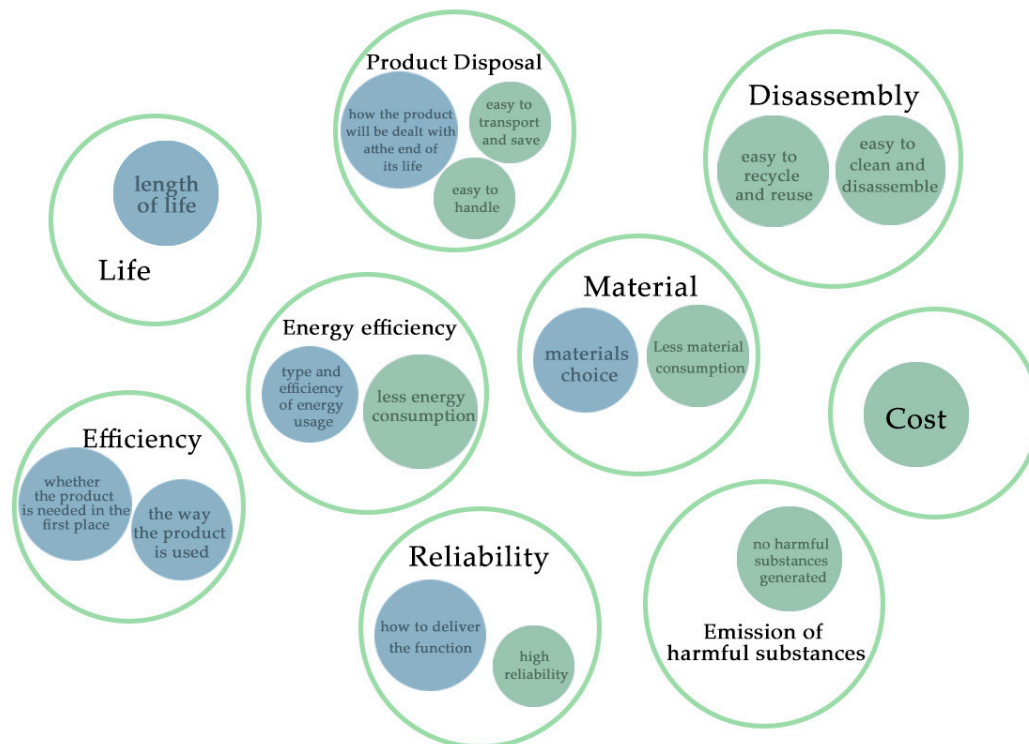


Figure 1. Summary of green factors.

- A. Energy efficiency: Energy is consumed during manufacturing and use, e.g., water resources, electricity, etc.
- B. Material: Evaluation of if it is renewable and reusable, including the total material consumption, as well as the weight, dimensions, and other factors related to it.
- C. Disassembly: Evaluation of if it is easy to disassemble and assemble at various stages of the life cycle.
- D. Life: Product service life, including product durability, fragility, etc.
- E. Emission of harmful substances: Evaluation of if substances may cause harm to the environment and human health during manufacture, use, and the end of life.
- F. Product Disposal: Evaluation of if the product can be easily stored and transported and the difficulty of disposal after scrapping.
- G. Efficiency: Evaluation of the degree of product function realization and work efficiency.
- H. Reliability: Evaluation of the product safety, tightness, etc.
- I. Cost: Include all running costs in the product's entire life cycle, such as manufacturing cost, labor cost, purchase cost, etc.

2.4. Integration of BioTRIZ and Green Factor Matrix

BioTRIZ may provide a good solution for a general product design, but it lacks the green design element in the model. However, the correlation between green factors and NEPs is usually inexplicit due to multiple NEPs' involvement at the same time. For this reason, Chen [9] attempted to establish a correlation table between seven environmental elements and the TRIZ EP, but the correlation strength was insufficient to be applicable. Ahmed [35] made some progress towards a strong correlation table between green factors and TRIZ EP for more quick and accurate parameter conversion.

In this paper, a matrix table of BioTRIZ and green factors is integrated for green factors to be effectively transformed into the related NEPs, and then the corresponding operational field can be obtained. Three green factors—durability, product disposal, and efficiency—over NEP were used for extensive case analysis of the green design contradiction resolution. A partial case analysis of green factors and the related NEPs is shown in Table 3.

Table 3. Case analysis of green factors and the related NEPs.

Green Factor	Related NEP	Example Application	References
Life	Stability	The chain drive of a bicycle is changed to gear drive, which prolongs the service life of the drive system	Ren and Tang [36]
Product Disposal	Complexity	The keyboard of the notebook uses a buckle instead of a thread connection; the newly fixed way reduces the disposal process in the scrap stage	Song et al. [37].
Efficiency	Shape	Increasing the power generation efficiency of solar cells by using light-transmitting mirrors	Chen [1]
...

3. Methodology

3.1. Problems Formation Using QFDE

Quality function deployment for environment (QFDE) can transform customer requirements into a green characteristics bounded at a satisfactory range [31]. Based on this principle, House of Quality (HOQ) is used as the core tool to carry out the transformation of customer requirements into technical characteristics [38]. First of all, the customer requirements for products can be obtained through market surveys. Therefore, standardization requirements can be obtained to determine the importance of the requirements. Second, the product's technical characteristics should be finalized from expert discussions. Then, both standardization requirements and technical characteristics are filled into the

corresponding locations in the HOQ. The correlation between two items is thus established, where 0, 1, 3, and 9 are used to indicate uncorrelated, weakly correlated, moderately correlated, and strongly correlated, respectively. The importance of the technical characteristics can therefore be calculated for the evaluation of further improvement of technical characteristics. In addition, the deterioration situation of technical characteristics can be found through the autocorrelation matrix of HOQ.

3.2. The Green Design Process

The green design process based on the BioTRIZ multi-contradiction resolution is shown in Figure 2. It contains four major steps. First, the customer requirements are converted into technical characteristics through QFDE. Second, the operational field is calculated using the BioTRIZ. Third, the IP based on the bionic principle is found from the BioTRIZ matrix. Finally, the design rationality is evaluated using the Rapid Life Cycle Assessment (RLCA) method.

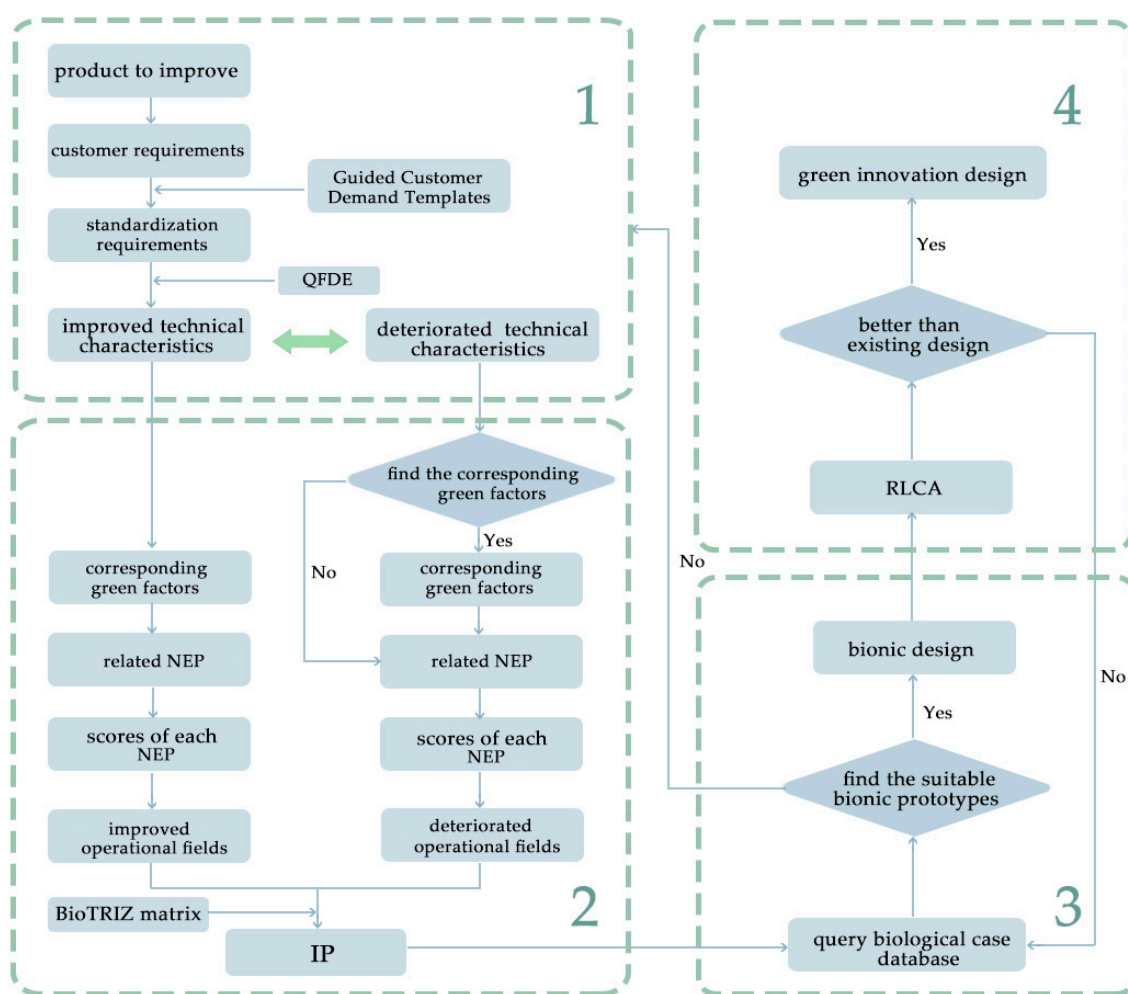


Figure 2. The green design process based on the BioTRIZ multi-contradiction resolution.

3.3. BioTRIZ Multi-Contradiction Resolution

In this study, the correlation between three green factors and NEP was therefore set up, and the corresponding correlation strengths between each other were scored using numbers from 0 to 10, where bigger numbers represent stronger correlations. For example, 0 means absolutely irrelevant, 10 is extremely correlated, and so on. In order to verify the validity of the results, a questionnaire survey was taken by a highly skilled team of BioTRIZ, including 26 teachers and 14 students. A total

of 40 questionnaires were filled out, and the statistical analysis of the data was carried out using SPSS software. The average value of the correlation between a green factor and the corresponding NEP was calculated by using the mean function of SPSS with a 1-10 strength correlation, where 0–1 means irrelevant, 1–4 is correlated, 4–7 is moderately correlated, and 7–10 is strongly correlated. The relationship between the green factors and BioTRIZ is listed in Table 4. The horizontal axis is the green factor, and the vertical axis indicates the six operational fields of BioTRIZ with the corresponding NEPs. Note that ● = 9 points, ○ = 3 points, and △ = 1 point, which indicate strong correlation, medium correlation, and weak correlation, respectively. However, the blank means no correlation. In addition, the blank space below A–I is used for filling with the technical characteristics. On the other hand, the blank space on the right side of I is a supplementary space for multiple characteristics to be filled.

Table 4. BioTRIZ and green factor matrix table.

	Fields	Green Factors									Score	Total Score
		A	B	C	D	E	F	G	H	I		
Importance												
S1	Weight	○	○	△			△		○			
	Loss of Substance				○	○	△		△	△		
	Amount of Substance	●	●	○	△	△	△		△	○		
S2	Stability			○	○	△	△	△	○	○		
	Complexity		△	○			○	○	○	○		
	Durability/Robustness/Life		△	○	●		○		○	△		
S3	Length		△	○				△				
	Area		○	○				△				
	Volume	○	○	○			△	△				
T	Shape			○	△		○	○	△			
	Speed	○			△			△	△			
	Productivity/Reproduction			○						○		
E2	Duration of Action				○		△	○		△		
	Force	△		○	△		○	△	○			
	Stress/Pressure	△		○	△		△	△	○			
	Strength		○		●		△		○			
	Temperature	●			△				△	○		
	Illumination Intensity/Brightness				○							
	Energy/Power	○					△	○		○		
	Function Efficiency	●				○		●		○		
I	Noise	△				○			○			
	Security/Protection/Vulnerability			△	○				●	○		
	Harmful Effects by System		△	○	○	○	△		○	△		
	Harmful Effects on System		△			●	○			△		
	Repairability/ Healing			○	○					○		
	Adaptability	△	△	△	○			○	○			
	Ability to Detect/Precision		△	○	△	○	△		△	△		
Amount of Information (Memory)	△	○	△				△		○			

Note: A: Energy efficiency; B: Material; C: Disassembly; D: Life; E: Emission of harmful substances; F: Product disposal; G: Efficiency; H: Reliability; I: cost; S1: Substance; S2: Structure; S3: Space; T: Time; E2: Energy; I: Information.

3.4. Design Evaluation

During the conceptual design stage, a reasonable evaluation process should be used to accurately determine whether the product is worthy to go ahead [39]. If environmental impacts (EIs) over the entire life cycle are initially taken into account, it may also improve the other design stages and achieve a better performance in the green product [14,40].

Life cycle assessment (LCA) is a major evaluation tool for green product design. However, the traditional LCA method usually requires large amounts data collected over a long term at the product's conceptual design stage. Therefore, Graedel [41] proposed a simplified and effective assessment method, i.e., the AT&T life cycle assessment, as shown in Table 5. This assessment includes five environmental factors, including materials chosen, energy efficiency, solid residues, liquid residues, and gaseous residues.

Table 5. The 5 × 5 assessment matrix proposed by AT&T [41].

Life Stages	Environmental Concerns				
	Materials Chosen	Energy	Solid Residues	Liquid Residues	Gaseous Residues
Pre-manufacture	1, 1	1, 2	1, 3	1, 4	1, 5
Product manufacture	2, 1	2, 2	2, 3	2, 4	2, 5
Product delivery	3, 1	3, 2	3, 3	3, 4	3, 5
Product use	4, 1	4, 2	4, 3	4, 4	4, 5
Refurbishment, recycling, disposal	5, 1	5, 2	5, 3	5, 4	5, 5

Note that in the result (x, y) as above x and y represent LCA evaluation score for original product and proposed product, respectively.

The Rapid Life Cycle Assessment (RLCA) method based on green features used in this study is developed to solve the inherent limitations of conventional LCA. Therefore, the sum (R_{erp}) of the evaluation matrices is defined as

$$R_{erp} = \sum_i \sum_j M_{ij} \quad (3)$$

where i is the environmental concern, j is the life stage, and M_{ij} is the sum of each environmental concern score in all life cycle stages. The matrix contains a total of 25 cells, where each cell has a value at the range of 1–5. A higher score means that the product is closer to a green product. During the conceptual design phase, this matrix provides an effective overall environmental assessment tool for product design.

4. Verification Using a Case Study

4.1. Practical Problem Formation Using QFDE

In this study, a window-cleaning robot is used as a case study to verify the effectiveness of the proposed method. As can be seen, the commercial product shown in Figure 3 still has some shortcomings, such as limited cleaning range and dependence on manual operation.

For the product design process, the QFDE principle is implemented at the first stage. First, customer requirements can be obtained through a market survey. Then, the green-related performance and its importance score can be determined, including the following major items: Efficient cleaning, human assistance, safety performance, weight, noise, energy efficiency, and cleaning cloth replacement. The customer requirements are standardized through the customer demand guide template, and technical characteristics are transformed through the HOQ process [39].



Figure 3. Commercial window-cleaning robot in the market.

The technical characteristics that need improvement or intend to decrease their importance score are concluded in Table 6. Among them, six technical characteristics that need improvement are summarized as: Mobile efficiency, labor cost, reliability, weight, noise, and energy efficiency. On the other hand, the moving efficiency and the complexity of the structure are a pair of negatively related technical characteristics. However, extracting the negatively related technical characteristics in HOQ, e.g., increasing the product's moving efficiency, may increase the complexity of the structure in reality.

Table 6. Table of characteristics over improvement and deterioration.

Characteristics to Be Improved	Characteristics to Be Deteriorated	Importance
Mobile efficiency	Structural complexity Number of parts	4
Energy efficiency	Harmful factors	1
Reliability	Other costs, Noise	2
Weight	Reliability	1
Labor costs	Disassembly, Number of parts	2
Noise	Reliability	1

4.2. Practical Solutions to Problems

To find the solutions based on BioTRIZ, the operational fields relevant to the technical characteristics that need to be improved are calculated first. Then, the green factors corresponding to each technical characteristic are found and added to the green factor boxes according to their attributes. Accordingly, the NEPs related to the technical characteristics to be improved are obtained and marked using $\sqrt{\quad}$, as shown in Table 7. Under the same procedure, the NEPs related to the technical characteristics to be deteriorated are also found, as shown in Table 8. The scores of the NEPs in each operational field are calculated and then added up to achieve the highest score of operational fields.

Consequently, the operational field O^+ = energy and the first deteriorated operational field O^- = structure for the window-cleaning robot design can be obtained to find a pair of major contradictions in energy and structure. The BioTRIZ matrix is queried, and then the proposed IP(energy vs. structure) is thus achieved as: 1, 3, 5, 6, 25, 35, 36, 40, as shown in Table 9.

Table 7. The correlations between the technical characteristics and improved NEPs.

Fields		Green Factors					Score	Total Score	
		A	B	E	G	H			I
		Energy Efficiency	Weight	Noise	Mobile Efficiency	Reliability			Labor Costs
	Importance	1	1	1	4	2	2		
S1	Weight	○	○√			○		3	3
	Loss of Substance			○		△	△		
	Amount of Substance	●	●	△		△	○		
S2	Stability			△	△√	○√	○	10	16
	Complexity		△		○	○	○√	6	
	Durability/Robustness/Life		△			○	△		
S3	Length		△		△				12
	Area		○		△				
	Volume	○	○		△				
	Shape				○√	△		12	
T	Speed	○			△	△			12
	Productivity/Reproduction						○		
	Duration of Action				○√		△	12	
E2	Force	△			△	○			66
	Stress/Pressure	△			△	○√		6	
	Strength		○			○			
	Temperature	●				△	○		
	Illumination Intensity/Brightness								
	Energy/Power	○√			○		○	3	
	Function Efficiency	●√		○√	●√		○√	54	
Noise	△		○√		○		3		
I	Security/Protection/Vulnerability					●√	○	18	20
	Harmful Effects by System		△	○		○	△		
	Harmful Effects on System		△	●				△	
	Repairability/ Healing						○		
	Adaptability	△	△		○	○			
	Ability to Detect/Precision		△	○		△√	△	2	
	Amount of Information (Memory)	△	○		△		○		

Note: S1: Substance; S2: Structure; S3: Space; T: Time; E2: Energy; I: Information.

Table 8. The correlations between the technical characteristics and deteriorated NEPs.

Fields		Green Factors				Structural Complexity	Number of Parts	Noise	Score	Total Score
		C	E	H	I					
		Disassembly	Harmful Factors	Reliability	Other Costs					
S1	Importance	2	1	2	2	6	4			
	Weight	Δ		○						
	Loss of Substance		○	Δ	Δ				36	
	Amount of Substance	○	Δ	Δ	○		9	36		
S2	Stability	○	Δ	○√	○√	1		18		
	Complexity	○√		○	○	9		70	88	
	Durability/Robustness/Life	○		○	Δ					
S3	Length	○								
	Area	○							6	
	Volume	○					3	6		
	Shape	○		Δ						
T	Speed			Δ						
	Productivity/Reproduction	○			○				0	
	Duration of Action				Δ					
E2	Force	○		○						
	Stress/Pressure	○		○√				6		
	Strength			○					30	
	Temperature			Δ	○					
	Illumination Intensity/Brightness									
	Energy/Power				○√			6		
	Function Efficiency		○		○					
Noise		○	○				9	18		
I	Security/Protection/Vulnerability	Δ		•√	○			18		
	Harmful Effects by System	○	○	○	Δ					
	Harmful Effects on System		○√		Δ			3	21	
	Repairability/ Healing	○			○					
	Adaptability	Δ		○						
	Ability to Detect/Precision	○	○	Δ	Δ					
	Amount of Information (Memory)	Δ			○					

Note: S1: Substance; S2: Structure; S3: Space; T: Time; E2: Energy; I: Information.

Table 9. BioTRIZ matrix.

Operational Field	Substance	Space	Structure	Time	Energy	Information
Substance	13, 15, 17, 20, 31, 40	1–3, 15, 24, 26	1, 5, 13, 15, 31	15, 19, 27, 29, 30	3, 6, 9, 25, 31, 35	3, 25, 26
Structure	3, 14, 15, 25	2–5, 10, 15, 19	4, 5, 36, 14, 17	1, 19, 29	1, 3, 4, 15, 19	3, 15, 21, 24
Space	1, 10, 15, 19	1, 15, 19, 24, 34	10	1, 2, 4	1, 2, 4	1, 3, 4, 15, 19, 24, 25, 35
Time	1, 3, 15, 20, 25, 28	1–4, 6, 15, 17, 19	1–4, 7, 38	2, 3, 11, 20, 26	3, 9, 15, 20, 22, 25	1–3, 10, 19, 23
Energy	1, 3, 13, 14, 17, 25, 31	1, 3, 5, 6, 25, 35, 36, 40	1, 3, 4, 15, 25	3, 10, 23, 25, 35	3, 5, 9, 22, 25, 32, 37	1, 3, 4, 15, 16, 25
Information	1, 6, 22	1, 3, 6, 18, 22, 24, 32, 34, 40	3, 20, 22, 25, 33	2, 3, 9, 17, 22	1, 3, 6, 22, 32	3, 10, 16, 23, 25

4.3. Bionic Design Solution

The original design of the window-cleaning robot suffers from an inflexible wipe that becomes helpless when hitting potholes. As learned from the biological case corresponding to the IP, a bionic design can be realized as follows. In the entry “merge” corresponding to IP 5, it is found that the biological phenomenon “cells are composed of two thin films at a distance of 10–20nm; therefore, a kind of air-bag-separating layer” can be forwarded to the design of window-cleaning robot. Based on this principle, the fluidity of the cell membrane is applied to make the window-cleaning cloth “float” using a fiber material instead of a rubber one. Greater flexibility can therefore be achieved. The profile comparison between floating and ordinary wipes is shown in Figure 4. It can be seen that the floating wipe with fit elastic is superior to the ordinary one with a suspended gap.



Figure 4. Comparison between floating and ordinary wipes: (a) Floating wipe with fit elastic; (b) ordinary wipe with a suspended gap.

The “segmentation of the insect body” in the “segment” entry of IP 1 can be applied to the design of the window-cleaning robot. As the barrier in crossing from one glass to another is the most difficult design part for the window-cleaning robot, the segmentation of insect bodies can provide a solution for solving this problem. This idea inspires the shape and structure for the robot with a bionic ability like an insect, greatly increasing the free mobile efficiency. Accordingly, the airframe of the proposed bionic robot is designed based on the leg section of a grasshopper, as shown in Figure 5. Note that the grasshopper legs and air-bag-separating layer are biological inspiration cases, but they are independent between each other.

The profile of the improved window-cleaning robot is shown in Figure 6. The ideas of air sacs between cell membranes and the insect body segmentation are delivered to the robot design. The middle disk is a suction module that can firmly adsorb on the window surface. The other two disks located at both sides are cleaning modules with the fiber wipe and suction capability. The robot arm connects with the suction module and two cleaning modules. It can also rotate 180 degrees in order to easily cross the barriers to different glass panes. The moving efficiency is thus enhanced.

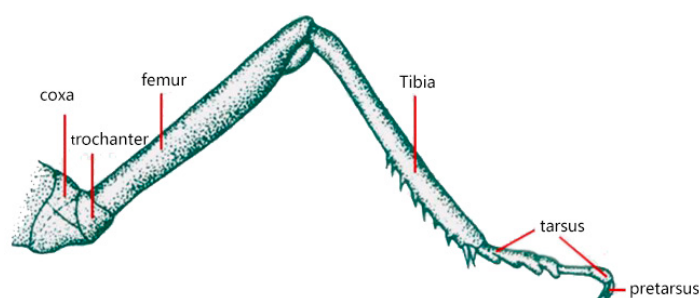


Figure 5. Profile of grasshopper leg section.



Figure 6. Profile of the improved window-cleaning robot.

4.4. Design Evaluation Using the Window-Cleaning Robot

The product design using the window-cleaning robot was evaluated in five life cycle stages, as shown in Table 10.

Table 10. Relationship between customer requirements and engineering parameters (EPs).

Life Stages	Environmental Concerns				
	Materials Chosen	Energy Use	Solid Residues	Liquid Residues	Gaseous Residues
Pre-manufacture	2, 3	2, 4	2, 3	2, 3	2, 3
Product manufacture	2, 3	2, 4	2, 3	2, 3	2, 3
Product delivery	3, 3	3, 3	3, 3	3, 4	3, 3
Product use	3, 4	3, 4	3, 3	3, 4	3, 3
Refurbishment, recycling, disposal	2, 4	2, 4	3, 3	2, 3	2, 3

Note that in the result (x, y) as above x and y represent RLCA evaluation score for original product and proposed product, respectively.

As shown above, it is found that the RLCA evaluation score reaches up to 83, while the original product score reaches only 61. It confirms that the feasibility of the proposed product design is enhanced.

5. Conclusions

Sustainability is one of the critical challenges on Earth, affecting all people in some ways, such as through economies and ecologies. As a result of this importance, green design is now a leading environmentally sustainable method to comply with the principles of economic, social, and ecological sustainability. At present, the design process based on BioTRIZ can solve a single contradiction-dominated problem efficiently, but solutions under multiple contradictions have not been fully unveiled in this field. This paper has successfully developed a BioTRIZ multi-contradiction resolution method by establishing a green factor matrix table and determining the green factors more quickly and accurately. Subsequently, the design process steps can be reduced significantly. By analyzing all contradiction information, the operational fields can also be obtained to increase the design efficiency. The window-cleaning robot design used as a case study confirms the effectiveness of the proposed method in terms of a simple, accurate, and fast process. In future work, the evolutionary

theory based on survival of the fittest of natural creatures may lead green product design. Therefore, the TRIZ evolution model may be integrated into a biological evolution to bring more green design inspiration into industry.

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