Article

Anticipatory Non-Green-Phenomena Determination for Designing Eco-Design Products

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Abstract: The number of consumers with green awareness have grown these days and as a result they have turned to purchase eco-friendly products. For this reason, this study aims to propose a method for eco-design based on the anticipatory failure determination method to develop eco-design products. By using eco-design concepts adopted from the World Business Council for Sustainable Development, the process will limit the failures and issues related to environmental impact in product design. The proposed method for eco-design product in this study follows the following procedure. First, we analyze product failure. Second, we propose the determination of the non-green phenomenon of the failure. Thirdly, we integrate the intensified non-green phenomenon to generate non-green hypotheses and fourthly, we eliminate each non-green phenomenon hypothesis by introducing the contradiction matrix of TRIZ for obtaining solutions. Finally, we assess alternative eco-design solutions by evaluation. To verify the practicality of the new procedure, a washing machine is used as an example for illustration.

Keywords: anticipatory failure determination; eco-design; TRIZ

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1. Introduction

Nowadays, consumers, manufacturers, procurers and even governments are more aware of environmentally friendly products, tasks and policies [1–5]. According to Hozik [6], the rate of Millennials willing to pay more for environmentally conscious products increased from 55% in 2014 to 72% in 2015. Curtin [7] had a similar report and stated that while 66% of global consumers were willing to pay more for sustainable goods (which included environmental, social and economic concerns [8–10]; however, this study focuses on environmentally friendly products or eco-design products more), a full 73% of Millennials (those born from year 1977 to 1995) were. According to Jezerc [11] from First Insight, Inc., 54% of Generation Z (born 1995–2012) were willing to spend an incremental 10% or more on sustainable products, versus 50% of Millennials (1980–1994), 34% of Generation X (1965–1979), 23% of Baby Boomers (1946–1964) and 36% of the Silent Generation (1928–1945). Actually, younger people have more expectations for eco-design products and various people of different ages also have a certain percentage to support them. Therefore, environmentally related concepts should be considered when developing products [11,12]. The World Business Council for Sustainable Development [13] pointed out that companies should consider environmentally friendly aspects when developing products and change their processes by applying environmentally related actions. Eco-design is important in the manufacturing industry and several design methods and tools have been developed to support eco-design [14].

In this study, important requirements will be identified for supporting the eco-design of a product. The important requirements of eco-design are minimizing resource use (such as energy efficiency and water consumption, etc.) [15], not damaging the environment [16],

etc. Moreover, Eltayeb et al. [17] mentioned basic eco-design activities, including design for reduction or elimination of environmentally hazardous materials, design for reuse, design for recycling, design for remanufacturing and design for resource efficiency, which can be derived for design requirements. In addition, full coverage of requirements for eco-design should be considered during the product life cycle stages [8,13,18]: extraction and processing of raw materials, manufacturing, transportation/distribution, use/reuse/maintenance and disposal/waste recovery stages. When the compliance of any of these requirements or regulations from different product life cycle stages fails, people will pay more attention to it. We call this kind of failure the non-green phenomenon, which means that a failure phenomenon occurs. This failure happens due to failures in the regulation of the eco-design or green design requirements in different product life cycle stages. This study will propose a design process to avoid these failures.

On the other hand, failures have always been a problem whether in product, system or even process design. Their increasing frequency and severity cause human suffering and damage to companies. The Anticipatory Failure Determination (AFD) is an efficient and effective method for analyzing, predicting and eliminating failures in systems, products and processes [19]. It is a cost-effective method of analyzing and predicting failures in products and processes. It guides users in documenting the situation, formulating related problems, developing hypotheses, verifying potential failure scenarios and finding solutions to prevent or eliminate the problems [20].

There are many case studies to illustrate AFD, and the following are some examples. Proseanic et al. [21] discussed the results of the AFD application in solving a hitching/ringing problem in an engine. Sunday [22] integrated the axiomatic design method with AFD to solve failure problems. Wang and Qiu [23] used the AFD method to find the failure conditions of an electrical motorcycle. Although AFD has been used in many studies, few studies use AFD for eco-design. For this reason, this study finds an opportunity to pursue research integrating AFD and eco-design elements for developing eco-design products.

This study aims to develop a method for green product design based on the principle of the AFD method and TRIZ tools. TRIZ is an inventive problem-solving theory and its tools will work with the AFD method to provide innovative solutions to help designers eliminate non-green phenomena in the product design, which will let the product comply with the requirements of eco-design. The rest of the paper is structured as follows: Section 2 gives the literature review, Section 3 details the methodology proposed in this study, Section 4 gives a washing machine design case study to demonstrate the practicality of the method and lastly Section 5 concludes the paper.

2. Literature Review

In this section, we will review literature under the following subjects: TRIZ, AFD and eco-design.

2.1. TRIZ

TRIZ is a Russian language acronym for *Teoriya Resheniya Izobreatatelskikh Zadatch*. Translated into English it means “The Theory of Inventive Problem Solving”. TRIZ is a theory invented by G.S. Altshuller and his colleagues between 1946 and 1985 [24]. TRIZ is a problem-solving method based on logic and data, not intuition, which accelerates a project team’s ability to solve problems creatively [25]. Several TRIZ tools now available in literature including Function and Attribute Analysis (FAA), Cause Effect Chain Analysis (CECA), Contradiction Matrix, Inventive Principles, S-Field, Trimming, Trends, Subversion Analysis, etc. However, this study will be using two TRIZ tools which are 40 inventive principles and a contradiction matrix. The TRIZ implementation process generally involves a series of steps, from a specific problem to the model of the problem via the innovation tool of TRIZ to obtain the model of solutions, so that a specific solution can be developed, as shown in Figure 1.

Figure 1. TRIZ implementation process [24].

2.2. Anticipatory Failure Determination

The anticipatory failure determination method was developed by Zlotin and Zusman [26]. It is based on the concepts that were called “subversion analysis” in earlier TRIZ work by Zlotin, Zusman, Altshuller, and Filatov [27,28] and Kaplan [29]. With the knowledge of how to subvert the design, the product designer can make the design better, so that the failures cannot happen [30]. The main objective of AFD is to “identify and bring to awareness, potential scenarios that could lead to systems and operations failure, so that they may be fixed before they actually occur” [13,31]. The AFD system consists of two modules: failure analysis of previous failures and prediction of failures that might occur in the future [15]. Ungvari [30] compared AFD with FMEA (Failure Mode and Effect Analysis) and noted that AFD differed from traditional failure analysis in transforming the idea of preventing failure into inventing and creating failures. Proseanic et al. [26] applied AFD to the analysis of the car engine, noticed that using AFD significantly reduced the time of brainstorming and increased the efficiency of the team. In addition, Chybowski et al. [32] applied three elements of the AFD method (AFD-1, AFD-2, and AFD-3) at the concept formulation stage of a system’s development for improving the technology readiness level. Most of the studies on AFD focus on solving the technical problems of products. This study will consider combining AFD with eco-design concepts. The concept of eco-design innovation has a lot of room for development, so applying other TRIZ tools will also contribute the improvement of the development of an eco-design product.

2.3. Eco-Design

Ecological design (Eco-design), also known as environmental design or green design, is an approach to designing products or processes that considers environmental impacts of the product during its whole life cycle [33]. An environmentally friendly technology leads to a reduction in the consumption of materials and energy. Andrae et al. [34] discussed that consumer electronics industry has a motivation on branding and making the eco-friendly image to respond to the increasing market share among the eco-aware consumers. In addition, Ferrendier et al. [35] mentioned that 70% to 80% of the development cost for most products is decided in early design phases. To achieve sustainable development goals, it is necessary to improve environmental efficiency and make good use of environmental resources.

In eco-design, the environment is given the same status as more traditional industrial values such as profit, functionality, aesthetics, ergonomics, image and overall quality [35]. Clark et al. [36] stated that having an eco-friendly material is one of the concepts that can help inspire new product design. Using waste as a valuable resource in the manufacturing will reduce harm on the environment. To save energy and avoid the abuse of materials, the design needs to consider the extension of product life, and implement green design concept and principles [37]. Besides applying to product design, the concept of eco-friendly can also be applied to other areas, such as production [38,39], packaging [40], ICT innovation [41], construction [42–44] and scrap tire handling [45].

According to DeSimone and Popoff [12], environmental-related concepts should be considered when developing products. According to Kibert [46], the World Business Council for Sustainable Development (WBCSD) points out that companies should consider

environmentally friendly aspects when developing products, and change processes by applying environmental-related actions. From a product life point of view, in 1991, WBCSD proposed seven eco-efficiency elements [13]: (1) reduce the material intensity of its goods and services, (2) reduce the energy intensity of its goods and services, (3) reduce the dispersion of any toxic materials, (4) enhance the recyclability of its materials, (5) maximize the sustainable use of renewable resources, (6) extend the durability of its products, and (7) increase the service intensity of its goods and services. These seven elements concern with three following broad objectives: (1) reducing the consumption of resources, (2) reducing the impact on nature, and (3) increasing product or service value.

Compared with the researches [8,13,17] in the literature, this study will consider the above seven eco-efficiency elements as eco-design requirements in the product design process, due to their originality and coming from WBCSD. When a failure or problem occurs against any of these requirements, a non-green phenomenon will be raised for the treatment of the AFD method.

3. Methodology

This study develops a problem-solving method based on AFD. This process can be done through analysis of the current products' non-green phenomena using AFD's reverse thinking by considering eco-design concepts. TRIZ problem-solving tool is used to solve the problem and determine the solution.

3.1. Non-Green Phenomenon

As discussed in the literature, WBCSD proposed seven eco-friendly elements or eco-design requirements, as shown in the following, and they can be presented in a shorter form in the parenthesis [13,47]:

- (1) Reduce the material intensity of its goods and services (Reduce material intensity)
- (2) Reduce the energy intensity of its goods and services (Energy intensity minimized)
- (3) Reduce the dispersion of any toxic materials (Dispersion of toxic substances is reduced)
- (4) Enhance the recyclability of its materials (Undertake recycling)
- (5) Maximize the sustainable use of renewable resources (Capitalize on use of renewables)
- (6) Extend the durability of its products (Extend product durability)
- (7) Increase the service intensity of its goods and services (Service intensity is increased).

This study will use these eco-design requirements as the criteria to determine whether a product has harmful impacts to the environment. If the answer is yes, then we will treat each of these impacts as a failure or problem as non-green phenomenon to be resolved in our proposed methodology. The idea involves using a list of seven requirements to allow designers or problem-solvers to check systematically to make sure that their products are environmentally friendly. Usually, these problems can be identified from consumers of the current products or the next generation products.

3.2. Problem-Solving Process

The method integrates AFD, contradiction matrix and eco-design elements to design green products. The idea is that when a product or system has a non-green problem, then it can be treated as a failure to be taken care. Once the failure is identified, the AFD method can be used. In addition, this study considers eco-design concepts in the product or system design process. In order to focus our proposal, the process will limit failures and issues related to the environmental impact of a product using the steps shown in Figure 2: (1) Failure analysis, (2) Determination of the cause, effect and non-green phenomena (NGP) of the failure, (3) Intensification of NGP and generate failure hypotheses from the results of the NGP Intensification, (4) Elimination of failures using contradiction matrix and (5) Assessment of alternative solutions. The process steps are explained in detail in the following.

Figure 2. Proposed problem analysis and problem-solving process.

Step 1: Failure Analysis

The objective of the first step is to identify the failures being experienced by the product for different product life cycle stages, which include extraction and processing of raw materials, manufacturing, transportation/distribution, use/reuse/maintenance and disposal/waste recovery stages. In this part, failures/problems will be determined in the product failure analysis table. At the same time, product details like product name, product illustration, product components, primary useful function and useful functions will also be shown. The failures determined in this step will be used during the next step in determining the non-green phenomena of each failure.

Step 2: Determination of the Cause, Effect and Non-Green Phenomena (NGP) of the Failure

The second step is done through an analysis of failures to determine their causes and effects. Each failure will be analyzed separately and will have a different table. The non-green phenomena (NGP) of each problem will be determined by considering the seven eco-design elements of eco-efficiency to eliminate the different aspects of a product that may cause environmental impacts including: materials use, energy use, hazardous substances, recyclability, total product life and service intensity i.e., a non-green phenomenon. A NGP of a product failure is any phenomenon/function that violates the eco-design concepts given above in relation to the failure/problem, e.g., high energy consumption, toxic emission, service degradation, etc. The product failures/problems determined from the previous step will be analyzed considering the seven eco-design concepts to determine

if they have non-green phenomena so that they can be eliminated. The NGP will be labeled as “NGP A1, NGP A2” depending on how many NGPs are determined for Failure A. According to DeSimone and Popoff [12], the greater the improvement in each of the seven eco-design elements, the more eco-efficient a product or process is.

Step 3: Intensification of NGP and Generate Failure Hypotheses from the Results of the NGP Intensification

This step focuses on intensifying the identified NGP. Based on the AFD concept of Kaplan et al. [30], the intensity of a harmful effect or undesired issues encountered is increased intentionally. Meanwhile, the NGP hypotheses are found by intensifying the NGP. In this step, the question of “how can the NGP be worsen” is asked to come up with the NGP hypotheses. The NGP hypotheses that are determined in this step will be used as a basis for the next step for prevention or elimination.

Step 4: Elimination of NGP Hypothesis with the Use of TRIZ Contradiction Matrix

In this step, the non-green hypothesis will be eliminated using the contradiction matrix with if-then-but rule. If the non-green hypothesis is eliminated, then the improving parameter is obtained, but the worsening parameter is also happened. From the contradiction, we can find the inventive principles suggested at their intersection in the Contradiction Matrix, as shown in Table 1 [24], which is defined by 40 inventive principles (Table 2) [24] and 39 engineering parameters (Table 3) [24]. These inventive principles will give solution triggers based on the knowledge of designers who solved similar problems before.

Table 1. Contradiction matrix [24].

Worsening parameters Improving parameters		1	2		39
		weight of moving object	weight of stationary object		productivity
1	weight of moving object		-		35, 3, 24, 37
2	weight of stationary object	-			1, 28, 15, 35
⋮	⋮	⋮	⋮		⋮
39	productivity	35, 26, 24, 37	28, 27, 15, 3		

Table 2. 40 Inventive Principles [24].

40 Inventive Principles					
1	Segmentation	15	Dynamics	29	Pneumatics and hydraulics
2	Take-out	16	Partial or excessive action	30	Flexible shells and Thin films
3	Local quality	17	Another dimension	31	Porous materials
4	Asymmetry	18	Mechanical vibration	32	Colors changes
5	Merging	19	Periodic action	33	Homogeneity
6	Universality	20	Continuity of useful action	34	Discarding and recovering
7	Nested Doll	21	Rushing through	35	Parameter changes
8	Counterweight	22	Blessing in disguise	36	Phase transitions
9	Preliminary anti-action	23	Feedback	37	Thermal expansion
10	Prior action	24	Intermediary	38	Strong oxidants
11	Cushion in advance	25	Self-service	39	Inert atmosphere
12	Equipotentiality	26	Copying	40	Composite materials
13	The other way around	27	Cheap, disposable objects		
14	Spheroidality/Curvature	28	Mechanics substitution		

Table 3. 39 engineering parameters [24].

39 Engineering Parameters					
1	weight of moving object	14	strength	27	reliability
2	weight of stationary object	15	duration of action by a moving object	28	measurement accuracy
3	length of moving object	16	duration of action by a stationary object	29	manufacturing precision
4	length of stationary object	17	temperature	30	external harm affects the object
5	area of moving object	18	illumination intensity	31	object-generated harmful factors
6	area of stationary object	19	use of energy by moving object	32	ease of manufacture
7	volume of moving object	20	use of energy by stationary object	33	ease of operation
8	volume of stationary object	21	power	34	ease of repair
9	speed	22	loss of energy	35	adaptability or versatility
10	force	23	loss of substance	36	device complexity
11	stress or pressure	24	loss of information	37	difficulty of detecting and measuring
12	shape	25	loss of time	38	extent of automation
13	stability of the object's composition	26	quantity of substance	39	productivity

Step 5: Assessment of Alternative Solutions

The possible alternative solutions will be evaluated using the five assessment criteria, which are product functionality, energy consumption, operation convenience, ease of manufacture and cost. For each criterion, three levels and their descriptions are written. Table 4 shows the scoring rubric.

Table 4. Scoring rubric for the criteria.

Criteria	1—Poor	3—Average	9—Excellent
Product functionality	Poor functionality	Average functionality	Excellent functionality
Energy consumption	High energy consumption	Average energy consumption	Low energy consumption
Operation convenience	Difficult to operate.	Can tolerate the complexity of operation.	Easy to operate.
Ease of manufacture	Difficult to manufacture.	Can tolerate the complexity of manufacture.	Easy to manufacture.
Cost	High cost	Reasonable cost	Low cost

In Table 4, the solution scales of one (1), three (3) and nine (9) represent the performance of poor, average and excellent accordingly. The alternative solutions will be assessed corresponding to different criteria. The design of the new product will be based on the results of the assessment of the alternative solutions. However, after assessment there might be a need for the alternative solutions to be selected or combined, and it depends on the problem solvers' decision on which kind of solutions they want to implement. The problem solver will also decide the minimum total score of the alternative solutions he/she wants to use in creating the new product.

4. Case Study

A washing machine will be used to demonstrate the proposed methodology with five steps discussed in Section 3. The reason for selecting washing machine as a case study is because washing machine is very rich to be identified non-green phenomena [15].

Step 1: Failure Analysis

In this step, product details like product name, product illustration, product components, primary useful function, useful functions and failures/problems are listed in Table 5 together with the identified product failures, as shown in the following:

- A. Washing machine vibrates during the spin cycle.
- B. Excessive wrinkling of clothes because of not removing the clothes right away after washing.
- C. Too much detergent is used.

For demonstration purpose, here we only focus on the use stage of the product to improve eco-performance. As to other stages, they can be considered similarly.

Table 5. Product failure analysis.

Product Name	Product Illustration
Top load washing machine
Product components	
Tub (interior), Timer control, Water level control, Wash speed selector, Water supply hoses, Door (top cover), Drain hose, Water inlet valves, Water filter, Spin Pulley, Spin Assembly, Water pump, Water hose, Transmission, Motor, Agitator, Plug	
Primary useful function	
Washes clothes	
Useful function	
Removes stains	
Removes bad odor	
Failure/Problem	
A. Washing machine vibrates during the spin cycle.	
B. Excessive wrinkling of clothes because of not removing the clothes right away after the wash.	
C. Too much detergent is used.	

Step 2: Determination of the Cause, Effect and Non-Green Phenomena (NGP) of the Failure

The second step is done through analysis of failures to determine its cause and effects. Each failure will be analyzed separately. The non-green phenomena (NGP) of each failure/problem will be determined by considering the seven eco-design concepts. The three product failures stated in Table 5 will be analyzed in this step. Each failure/problem will be observed considering the seven eco-design requirements or eco-efficiency elements to determine the non-green phenomenon.

- a. How to generate NGP with the first failure/problem (A) which is “washing machine makes vibration during the spin cycle”?

As shown in Table 6, the cause of the failure is washer, not level, which results in making the washing machine out of balance and vibrating during use. This leads to one NGP, which is:

NGP A1: Parts have become worn out or loose.

As shown, the NGP is labeled as NGP A1 because it is from failure A. However, if there are two failures, then it will be labeled as NGP A1 and NGP A2. It depends on how many NGPs are determined. This will also be done on failure B, and the same with failure C. After Table 6, if there is no NGP corresponding to the eco-design requirements, then the empty space will be skipped for simplicity.

Table 6. Product failure analysis questionnaire for the failure/problem A.

Failure/Problem	A: Washing Machine Makes Vibration during Use
Cause of the failure/problem	Washer is not level.
Effect of the failure/problem	Washing machine gets out of balance.
Eco-design requirements:	NGP:
1. Reduce the material intensity of its goods and services	
2. Reduce the energy intensity of its goods and services	
3. Reduce the dispersion of any toxic materials	
4. Enhance the recyclability of its materials	
5. Maximize the sustainable use of renewable resources	
6. Extend the durability of its products	
7. Increase the service intensity of its goods and services	A1: Parts have become worn out or loose.

- b. How to generate NGP with the second failure/problem (B) which is “excessive wrinkling of clothes because of not removing the clothes right away after the wash”.

As shown in Table 7, excessive wrinkling of clothes because of not removing the clothes right away after the wash leads to two NGPs, which are:

NGP B1: Clothes should be rewashed to remove wrinkles, which will increase water consumption.

NGP B2: Clothes should be ironed in order to wear it immediately, which will increase energy consumption.

Table 7. Product failure analysis questionnaire for problem B.

Failure/Problem	B. Excessive wrinkling of clothes because of not removing the clothes right away after the wash.
Cause of the failure/problem	Accidentally forgets to remove the clothes from the washer right away when the wash is done.
Effect of the failure/problem	Clothes can't be used immediately after drying.
Eco-design requirements:	NGP:
2. Reduce the energy intensity of its goods and services	B1: Clothes should be rewashed to remove wrinkles, which will increase water consumption. B2: Clothes should be ironed in order to wear it immediately, which will increase energy consumption.

- c. How to generate NGP with the third failure/problem (C) which is “too much detergent is used”?

As shown in Table 8, the third failure/problem (C) which is “too much detergent is used” leads to one NGP:

NGP C1: Clothes will not be properly rinsed.

Table 8. Product failure analysis questionnaire for problem C.

Failure/Problem	C. Too much detergent is used.
Cause of the failure/problem	No measuring tools. The user is just a beginner.
Effect of the failure/problem	Suds will be left on the clothes.
Eco-design requirements:	NGP:
7. Increase the service intensity of its goods and services	C1. Clothes will not be properly rinsed.

After converting from problems or failures, all the NGPs are summarized in Table 9.

Table 9. Summary of the identified NGPs.

Failure/Problem	Non-Green Phenomenon
A. Washing machine vibrates during the spin cycle.	NGP A1: Parts have become worn out or loose.
B. Excessive wrinkling of clothes because of not removing the clothes right away after the wash.	NGP B1: Clothes should be rewashed to remove wrinkles, which will increase water consumption. NGP B2: Clothes should be ironed in order to wear them immediately, which will increase energy consumption.
C. Too much detergent is used.	NGP C1: Clothes will not be properly rinsed.

Step 3: Intensification of NGP and Generation of Failure Hypotheses from the Results of the NGP Intensification

This part focuses on intensifying the identified NGP. In this step the question “how can the NGP be worsened?” is asked to come up with the NGP hypotheses as shown in Table 10. For example, for NGP A1: parts have become worn out or loose, its intensification will be “parts will completely loosen” (Hypothesis 1, H1), then we will have the result of “the whole washing machine will be broken”. For NGP B1: clothes should be rewashed to remove wrinkles, which will increase water consumption. If lower water temperature is used (H2) [48] and faster spin speed is used (H3), then wrinkles get even worse.

Table 10. Intensification of non-green phenomenon.

Failure/Problem	Non-Green Phenomenon	Item That Relates to the NGP	How to Make the NGP Even Worse? (NGP Hypothesis)	Result
A. Washing machine vibrates during the spin cycle.	NGP A1: Parts have become worn out or loose.	Vibration	Parts will completely loosen. (H1)	Whole washing machine will be broken.
B. Excessive wrinkling of clothes because of not removing the clothes right away after the wash.	NGP B1: Clothes should be rewashed to remove wrinkles, which will increase water consumption.	Water	Used colder water. (H2)	Wrinkles get worse.
			Used faster spin speed. (H3)	Wrinkles get worse & use more electricity.
	NGP B2: Clothes should be ironed in order to wear them immediately, which will increase energy consumption.	Electricity	Takes longer ironing time because of excessive wrinkles. (H4)	Clothes will be damaged. Uses more electricity.
C. Too much detergent is used.	NGP C1: Clothes will not be properly rinsed.	Clothes	Accidentally put in the whole detergent. (H5)	Bubbles will overflow. Clothes will be damaged because more water will be used to rinse.

Step 4: Prevention/Elimination of NGP Hypothesis with the Use of TRIZ Tools

In this step, the non-green hypothesis happened in Step 3 will be eliminated using the contradiction matrix. The improving and worsening parameters will be used to find the inventive principles suggested from the contradiction matrix as shown in Table 11. For example, if we want to prevent Hypothesis 1: “prevent the parts from loosening”, then we have to make parts tight, which will improve the product strength (parameter 14); however, this is difficult to accomplish, which will worsen parameter 32 (ease of manufacture). From the contradiction matrix, we can find inventions 11 (Beforehand cushioning), 3 (Local quality), 10 (Preliminary action) and 32 (Color changes). These inventive principles can serve as solution triggers for the hypothesis developed from the intensification of the failure or problem.

Table 11. Inventive principles for each hypothesis.

Hyp.	Item	If (Prevention or Elimination of Non-Green Hypothesis/ Assumption)	Then (Improving Parameters)	But (Worsening Parameters)	Inventive Principles
H1	Vibration	Prevent the parts from loosening.	Make parts tight. (14. Strength)	Difficult to accomplish. (32. Ease of manufacture)	11. Beforehand cushioning 3. Local quality 10. Preliminary action 32. Color changes
H2	Water	Prevent wrinkles from getting worse by using warm water.	Reduce wrinkles. (39. Productivity)	Increase electricity consumption. (22. Loss of energy)	28. Replace a mechanical system 10. Preliminary action 29. Pneumatics or hydraulics 35. Physical or chemical properties
H3	Electricity	Prevent wrinkles from getting worse by using slower spin.	Reduce electricity consumption (22. Loss of energy)	Does not dry the clothes properly. (39. Productivity)	28. Replace a mechanical system 10. Preliminary action 29. Pneumatics or hydraulics 35. Physical or chemical properties
H4	Clothes	Eliminate wrinkles by using a powerful iron.	Less time to remove wrinkles. (27. Reliability)	Expensive. (38. Extent of automation)	11. Beforehand cushioning 13. 'The other way around' 27. Cheap short-living objects
H5	Clothes	Avoid putting in the whole detergent.	<ul style="list-style-type: none"> Makes the clothes last longer. Prevents the machine from being broken due to overflowing of bubbles. Conserves water. (27. Reliability) 	Need to install additional functions (36. Device complexity)	13. 'The other way around' 35. Parameter changes 1. Segmentation

In Table 11, the inventive principles for solving the failure/problem are determined. These will be used in Table 12 to find feasible solutions to the NGP of the problems. There are two solutions found for Hypothesis H1, H4, and H5, and one solution found for Hypothesis H2 and H3. In total, there are eight solutions found. The purpose of this study is to demonstrate how the product innovative process works, so the betterness of the solution is not our main concern, which will leave the product developer to make efforts.

Table 12. Possible solutions for the NGP hypothesis.

Hyp.	NGP Hypothesis	Inventive Principles	Possible Solutions
H1	Parts will completely loosen.	11. Beforehand cushioning 3. Local quality 10. Preliminary action 32. Color changes	Add built-in vibration reduction technology. (Solution No. 1-1) None Install an anti-vibration pad under the washing machine. (Solution No. 1-2) None
H2	Used higher water temperature.	28. Replace a mechanical system 10. Preliminary action 29. Pneumatics or hydraulics 35. Physical or chemical properties	None Install temperature sensors that can automatically control the water temperature to provide optimum washing performance. (Solution No. 2-1) None None

Table 12. Cont.

Hyp.	NGP Hypothesis	Inventive Principles	Possible Solutions
H3	Used faster spin speed.	28. Replace a mechanical system	None
		10. Preliminary action	Various spin speed and wash motions customized for different types of fabric. (Solution No. 3-1)
		29. Pneumatics or hydraulics	None
		35. Physical or chemical properties	None
H4	Takes longer ironing time because of excessive wrinkles.	11. Beforehand cushioning	None
		13. The other way round	Can get connected to the phone via Wi-Fi to get alerts when the wash is done. (Solution No. 4-1)
		27. Cheap short-living objects	Add an alarm that alerts the user when the wash is done. (Solution No. 4-2)
H5	Accidentally put in the whole detergent.	13. The other way round	A detergent/fabric conditioner dispenser that can sense the load size to determine the amount of detergent to release. (Solution No. 5-1)
		35. Parameter changes	None
		1. Segmentation	Add detergent tray that distributes detergent/fabric conditioner. (Solution No. 5-2)

Table 13 illustrates and summarizes the solutions shown in Table 12 so that it will be easy to evaluate them.

Table 13. Summarized solutions per NGP hypothesis.

Hyp.	Solution Number	Solution	Solution Illustration
H1	No. 1-1	Add built-in vibration reduction technology.	Add a technology such as VRT Plus technology [49]. Install anti-vibration pads [50].
	No. 1-2	Install an anti-vibration pad under the washing machine.
H2	No. 2-1	Temperature sensors that can automatically control the water temperature to provide optimum washing performance.	The sensors can have the following setting for different wash modes [51]: Cold 60 °F–80 °F Warm 80 °F–100 °F Hot 110 °F–140 °F.
H3	No. 3-1	Various spin speed and wash motions customized for different types of fabric.	See the reference [52].
H4	No. 4-1	Can get connected to the phone via Wi-Fi to get alerts when the wash is done.	Remote control using an app [53].
	No. 4-2	Add an alarm that alerts the user when the wash is done.	

Table 13. Cont.

Hyp.	Solution Number	Solution	Solution Illustration
H5	No. 5-1	A detergent/fabric conditioner dispenser that can sense the load size to determine the amount of detergent to release.	<p>Use a technology such as SmartDispense technology to automatically dispense detergent and fabric softener [54].</p>
	No. 5-2	Add detergent tray that distributes detergent/fabric conditioner.	<p>See the reference [55].</p>

Step 5: Assessment of Alternative Solutions

After finding possible alternative solutions, these will be evaluated using the five assessment criteria which are: product functionality, energy consumption, operation convenience, ease of manufacture and cost. The alternative solutions are assessed in Table 14. Each solution will be scored according to the different criteria.

Table 14. Assessment of alternative solutions.

		Criteria					
Solution Number		Product Functionality	Energy Consumption	Operation Convenience	Ease of Manufacture	Cost	Total Score
H1	No. 1-1	9	9	9	1	1	29
	No. 1-2	9	9	9	3	1	31
H2	No. 2-1	9	3	9	3	3	27
H3	No. 3-1	9	9	9	3	3	33
H4	No. 4-1	9	9	9	1	3	31
	No. 4-2	9	9	9	3	3	33
H5	No. 5-1	9	9	9	1	3	31
	No. 5-2	9	9	9	3	3	33

The design of the new product will be based from the results of the assessment of alternative solutions. Some solutions, such as No.5-1 and No. 5-2 are needed to choose one, but some solutions can be selected based on the developer's decision or customer's need. The product developer will also decide the minimum total score of the alternative solutions he/she wants to use in creating the new product.

5. Conclusions

This study examines the integration of AFD, environmental considerations and TRIZ tools to solve product failures to reduce the environmental impacts of product failure. A new green product design process with anticipatory non-green-phenomena determination was developed. The product failures were analyzed first to find non-green phenomenon. Then the NGP were intensified by thinking about how to make NGP worse to find the NGP hypotheses. Lastly, the contradiction matrix and inventive principles were used to eliminate the NGP hypotheses to improve the product eco-efficiency and discover

green design solutions. The washing machine was the product used to demonstrate the methodology and many eco-design solutions were derived for the washing machine product design. We believe that our methodology can serve as a reference to product designers to provide a systematic way of designing green products for their product life cycle (although only the use stage is demonstrated in our case study due to space limitation) and help designers in integration of AFD in green product design.

This study only concerns the green aspects in the product design process. In practice, it needs to incorporate other aspects, such as product function, cost and manufacturing, which will make more complete considerations. In recent years, circular economics [56–58] is also a new area to be considered when we are designing products.

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