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Risk Analysis of Green Supply Chain Using a Hybrid Multi-Criteria Decision Model: Evidence from Laptop Manufacturer Industry

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Abstract: Green supply chain management has become enormously significant over the last two decades. Traditional supply chain risk management is inept at dealing with the intangible criteria related to environmental issues. Contrary to most of the previous research, which emphasized risks in merely one or two phases of the green supply chain, this study provides a systematic checklist of the cradle-to-grave approach to risk identification and prioritization using a hybrid method. Based on a world-leading Taiwanese laptop manufacturer, we first identified the risk factors of the green supply chain with respect to the components and subcomponents of Risk Priority Numbers (RPN) on the Failure Mode and Effects Analysis (FMEA). Second, we used the Analytic Network Process (ANP) to derive the relative weights of the subcomponents of RPN. Third, we combined grey relational analysis and ANP weights to derive the relative importance of each risk criterion in each risk factor in the green supply chain. The empirical results verified that our proposed method can be applied to the laptop manufacturing industry and found industry-specific green risk criteria in each factor. Therefore, following this, enterprises can control the possible risks for continuous improvement in their green activities.

Keywords: RPN; FMEA; ANP; grey relational analysis; green supply chain

MSC: 90B50; 90C31; 90C99

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1. Introduction

Nowadays, Computers, Communications, and Consumer electronic (3C) products are discarded quickly because a new generation of intelligent devices is innovated in a short time. To overcome the increasing problem of 3C products being easily discarded, attempts are made to recycle, refurbish, or remanufacture discarded goods to provide secondary materials or reused products that can approximate the performance of new products. Therefore, in the green supply chain, the focus is on the entire process starting from material purchase, refurbishment, remanufacturing, and recycling of the disposal of goods. The more environment-friendly the company is, the more likely it is to invest in green management so that it can gain the trust of consumers and convince them of the brand and product's reliability, safety, and trustworthiness. Over a period, these efforts by the company will increase the consumers' purchase intention for green products, whereas environment-unfriendly products will gradually be weeded out of the market [1–4]. Green consumption drives companies to think about how to launch green products to meet customers' needs and environmental awareness at the same time, and to promote sustainability [5–8].

The functions of electronic products are becoming more and more diverse, and the high replacement rate and rapid update of products have led to the exponential growth of discarded electronic products. Without the most appropriate recycling method, the damage to the environment is unimaginable. Therefore, there is an urgent need for more effort and time to recycle and dispose of waste electrical and electronic equipment to minimize its severe consequences on the environment. As environmental protection and sustainability have become gradually rooted in human lives, many countries have begun to add different specifications to industries producing the 3C products. They began to amend relevant regulations to restrict product parts and manufacturing methods such as the Restriction of Hazardous Substance (RoHS) or Waste Electrical and Electronic Equipment (WEEE), Japan's Environmental Basic Law. In the same vein, Taiwan also has toxic chemical substance management laws and laws regulating resource recycling and disposal. In addition, more and more manufacturers are adopting Corporate Social Responsibility (CSR) rules which are over and above the relevant environmental laws, so that producers work closely with suppliers to meet the standards [9–11]. According to statistics provided by the Environmental Protection Agency, collected during the 1990s, the number of recycled waste notebooks per year has increased steadily in Taiwan, and the amount of waste carbon emission from reused notebooks is likely to increase in the future. Therefore, the refurbishing process from purchasing parts, and processing and remanufacturing reused notebooks, requires an appropriate evaluation to ensure an environment-friendly production process. However, there are many risks and uncertainties in the process of a green supply chain, and, especially, the process by which one can evaluate the risks generated in the green supply chain is relatively difficult for both producers and suppliers.

In the field of risk research, supply chain risk management is an increasingly conspicuous topic [12–23]. The process of the green supply chain needs to comply with the regulations passed by countries around the world. However, most of the environmental regulations in various countries have only matured in recent years and the standards are not the same. The purchase of components for refurbishing the collected products needs to be more cautious, and the defective rate may increase due to non-compliance during the production and assembly process. In Taiwan, some computer manufacturers are playing important roles in the laptop (notebook) market and have established a steady relationship with their suppliers for a long time. They have complied with environmental regulations such as RoHS and WEEE. Because of the production material and procurement of parts, the manufacturing process, and logistics distribution and marketing, recovery and disposal may generate significant risks that can affect the entire operating system. Therefore, before conducting risk management of a green supply chain, enterprises should first understand the possibility of risk and the severity of the impact to predict the risk clearly.

Based on their study of 165 Finnish companies, Lintukangas et al. [24] found that significant costs and price risk management averted companies from adopting green supply chains. Moreover, they found high-spending companies to be less willing to adopt green supply chains. However, compared to traditional supply chain management, green supply chain management is less comprehensive with respect to risk management. The extant literature mostly focuses on risks arising in one or two phases of the green supply chain [25]. Nevertheless, the risks associated with a closed-loop green supply chain have not been extensively identified and prioritized, especially in the five phases of a laptop computer's lifespan. Therefore, in this study, we attempted to make substantial contributions to green supply chain risk management by identifying the laptop industry-specific risks and ranking the significance of risks throughout a five-phase closed-looped supply chain which spans the entire product lifetime from green design, green procurement, green manufacturing process, green marketing, and green recovery, concerning the five factors of risks.

In this study, we aimed to explore green supply chain management from risk definition, risk assessment, and risk analysis to achieve effective green supply chain risk management from the perspectives of internal and external infrastructure, thus integrating enterprises with customers' green concerns. To minimize the impact of these risks in green supply chain activities, we tried to define the components and subcomponents of the Risk Priority Number (RPN) based on the Failure Mode and Effects Analysis (FMEA) concerning the green risk factors. The research goals are summarized as follows:

1. Define the risk factors in the green supply chain;

2. Construct the subcomponents based on the RPN components defined by the FMEA;
3. Calculate the weights of subcomponents for each RPN component by using ANP;
4. Rank the evaluated criteria for each risk factor based on the weight of subcomponents in each component of RPN;
5. List the major criteria for each risk factor for continuous improvement.

2. Literature Review

In 2000, a sudden strike at Philips's Mexico plant caused an unexpected shortage of supplies of materials and components, resulting in a loss of USD 400 million for a single source of telecommunications. The company's market share fell from 12% to 9%. If we analyze the series of events leading to the strike, we can conclude that the main risk in the supply chain was attributed to single suppliers, dominating vendors, national risk, suppliers with the poor financial condition, the company's failure to cooperate with suppliers, high transaction complexity, and a high rate of outsourcing. As per Hervani et al. [26], the supply chain ideally provides high-capacity, fast and efficient services to meet customers' needs through organizational operations without leading to continuous changes in risk distribution. Several critical events such as natural disasters, labor disputes, supplier bankruptcy, war, and terrorism cause risks in a supply chain by bringing in inaccurate raw material, parts forecast with delayed shipments, lost sales, increased costs, failed procurement, and inventory corrections [27].

According to Chemweno et al. [28], supply chain risks can be broadly classified into environmental risks, organizational risks, and cyber and collaboration risks. Samvedi et al. [17] classified supply chain risks into supply risks (such as outsourcing risks, supplier failures, quality, and sudden rises in costs), demand risks (such as sudden reversals in the business climate, changes in market demand, changes in competition, and prediction errors), process risks (such as machine failures, labor disputes, quality issues, technological changes), and environmental risks (such as terrorism, natural disasters, economic recession, and social and cultural movements). To effectively measure the risk factors existing in the green supply chain, in this study, we reviewed the relevant literature for assessing risk. In green supply chain management, we found that a company should choose environmentally-friendly raw materials and components, and the company must have the ability to control the risk of choosing materials from unknown origins and of uneven quality to save production costs [20,29,30]. Hervani et al. [26] defined a green supply chain as:

Green Supply Chain Management = Green Purchasing + Green Management (Material Management) + Green Distribution (Marketing) + Reverse Logistics.

Hervani et al. [26] also suggested that several studies have considered the concept of ecological sustainability while emphasising the role of different elements of production process design and material procurement in integrating green factors into management practices before reflecting on the relationship between supply chain management and the natural environment. Therefore, in addition to the benefits derived from recycled materials or the improvement of the production process that ensures lesser carbon emission, the greater benefit accrued is in reduced toxic substances in the product's life cycle assessment. Therefore, the green supply chain can extend the traditional issues related to the supply chain from the perspective of enterprise responsibility by emphasizing quality, elasticity, speed, value, and service from the production process, as well as consumption processes and end-of-pipe processes. As per Steger [31], the green concept should be embedded in the management process and culture so that a direction of environmental development in the supply chain can be planned into a long-term strategy.

According to Green et al. [32], green supply chain management refers to the ways by which supply chain management innovation can be considered environmentally friendly. The most prominent paradigm of supply chain innovations is technological applications. The latest technological advancements such as artificial intelligence, blockchain, cloud computing, and the internet of things are acclaimed to ensure that supply chains are more sustainable and greener. Enterprises engaging in technological innovations can not only improve the environmental conditions of green supply chain activities with higher efficiency and efficacy but can also reinforce their internal and external cooperations with supply chain stakeholders [33–37]. Klassen and McLaughlin [38] suggested that environmental management has made efforts to minimize hazardous substances and emissions throughout the product life cycle. As per van Hoek [39], 'environmentally sustainable' has become an important organizational concept in green supply chain management as it focuses on reducing environmental risks and impacts and improving ecological benefits. According to Narasimhan and Carter [40], green supply chain management includes reduction, recycling, reuse, and material replacement. Further, Zsidisn and Siferd [41] defined the green supply chain as a process of implementing and adopting a set of supply chain management policies and actions, and echoing the relationship between the natural environment and design, procurement, production, distribution, use, and reuse.

Furthermore, Zhu and Sarkis [42] explored green supply chain management from a closed-loop perspective, ranging from green procurement to the supply chain, manufacturing, customer, and reverse logistics processes. As per Srivastava [43], green supply chain management encompasses product design, raw material procurement and selection, production process, and final product delivery to consumers, as well as end-of-life management. For Walker et al. [44], green supply chain management emphasises reducing packaging and waste, evaluating suppliers for their environmental performance, developing more environmentally friendly products, and reducing carbon emissions related to transportation.

Therefore, to sum up, a green supply chain integrates the green concept into traditional supply chain management. In addition to quality and flexibility, as emphasized by traditional supply chain management, in green supply chain management, the environmental issues related to the upstream of raw materials and the downstream consumers, with respect to product design, manufacturing, and distribution, are considered, in addition to reusing, recycling, and remanufacturing waste products. Based on the review of the extant literature, in this study, we identified five major factors of a green supply chain, and these are:

Green Design: to respond to the environmental protection trend, the green concept has been embedded in products from the stage of design, delivery, and product-using process to end-of-life disposal. Consequently, one could minimize the amount of waste sent to landfills by recycling, remanufacturing, and reusing parts and products.

Green Procurement: as hazardous substances are accumulated throughout the product manufacturing and use process, one should select green suppliers to purchase cleaning materials and components so that the end-of-life product complies with the relevant environmental protection regulations.

Green Manufacturing Process: given that environmental legislation is strictly enforced, most manufacturers would become responsible for their products in the entire life cycle. Therefore, after end-of-life, a responsible manufacturer would collect the disposed products for recycling, remanufacturing, and reusing them into secondary products.

Green Marketing: to meet the goal of a sustainable environment, most consumers are educated by the government or social media, and, as a result, they would prefer those manufacturers who strive for green activities. Therefore, consumers would have a better brand image than green manufacturers. As a result, the marketing strategy in the green supply chain would help a consumer to buy products that are environmentally friendly or else, without the concept of environmental awareness, green manufacturers would lose the opportunity to make profits as well as having their corporate image and reputation tarnished.

Green Recovery: the concept of recovery aims to minimize the waste sent to landfills by repairing, refurbishing, or remanufacturing the disposal products, or recycling the materials or components to make the secondary material and components.

Hallikas et al. [45] pointed out that risk can be broadly defined as danger, damage, and loss. The process of risk analysis is to provide enterprises with possible solutions for risks based on expert insights. FMEA is a systematic method for studying failure, which has been widely used in various types of industries, including the manufacturing, food and beverage, plastic production, software, and healthcare industries. The green supply chain strives for procurement and manufacturing processes that do not pollute the environment and, at the end of the final product life cycle, reverse logistics is used to recycle, remanufacture, and reuse the product to reduce waste.

According to Sharratt & Choong [46], environmental issues not only have a profound impact on corporate cost and profit, but compliance with environmental regulations leads to verifying whether the products produced are suspected of causing harm to the environment. Soon after negative news about a manufacturer comes out, most customers build a negative image of the company's brand. Thus, one needs to confirm and carefully manage the risk generated in a green supply chain. Here, FMEA can identify potential defects and their early degree of impact in the process of engineering design to seek solutions in order to avoid failure and curb the impact of its occurrence or reduction. Agrell et al. [47] explored uncertainty in demand levels, outsourcing, unstable relationships with partners, and uneven supply chain risk for telecommunications companies in a three-stage stochastic programming model. In addition, Wu et al. [48] used the AHP method to rank hierarchical risk factors in supply chain management. Wang et al. [49] developed a two-stage fuzzy AHP model to assess the risk of green awareness promotion in popular industry supply chains. Samvedi et al. [17] used fuzzy AHP and fuzzy TOPSIS to construct risk indicators to assess supply chain risks.

3. Materials and Methods

The multi-criteria decision-making model (MCDM) is a powerful tool to prioritize the limited alternatives based on selected criteria. In this study, we have taken advantage of the MCDM models to evaluate risk assessment using failure mode and effect analysis (FMEA) [50], Analytical Network Process (ANP) [51], and the Grey Relational Method (GRA) [52]. In this section, we explain our proposed framework. Based on the literature review, we understood that risk analysis in the green supply chain is as important as in the traditional supply chain. Therefore, we first defined the main risk factors from the literature review and then used a focus group to interview a few senior managers and engineers to define the risk criteria for each risk factor. Second, we used ANP to derive the weight of the RPN subcomponent in each component. Third, using the weights of each RPN subcomponent which supported the functionality of risk criteria, we evaluated the order of risk criteria in each risk factor using GRA. Finally, we established the priority of green risk criteria for each risk factor for continuous improvement in green supply chain management. The framework for finding the risk criteria in each risk factor has been elaborated in Figure 1.

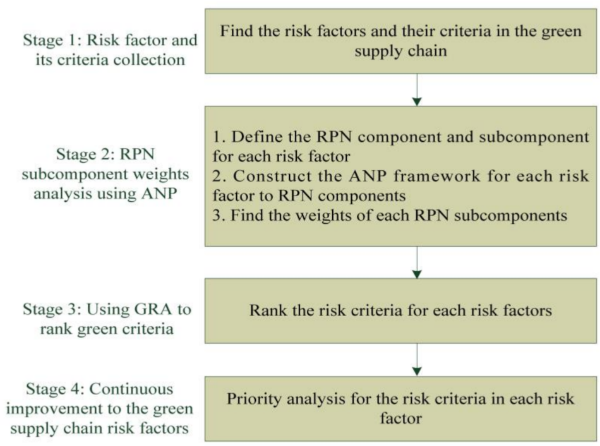

Figure 1. The framework of the proposed methodology.

According to the framework, as shown in Figure 1, the methodology used for risk analysis in green supply chain management is explained in the following subsections.

3.1. Failure Mode and Effect Analysis (FMEA)

The Failure Mode and Effect Analysis (FMEA) methodology is organized around the cause-and-effect failure modes and is a widely-used reliability tool for risk analysis as recommended by international standards agencies such as the Society of Automotive Engineers, the US Military of Defense, and the Automotive Industry Action Group. The basic function of FMEA is to find, prioritize, and minimize failure. It has been widely used in manufacturing areas in solving reliability-related problems [2,53,54]. FMEA is one of the most common methods to analyze risk and, despite its shortcomings, it can maximize the satisfaction of customers by eliminating and/or reducing known or potential problems [55]. This method increases the quality of the product and productivity of the service, the system, and the event [56]. FMEA considers three risk components which are usually evaluated through easily interpreted linguistic expressions: severity (S), occurrence (O), and detection (D). These are measured on a scale from 1 to 10 points. The Severity measures the seriousness of the effects of a failure mode. The Occurrence is related to the probability of a failure mode occurring.The Detection captures a failure's visibility, or the attitude of a failure mode as identified by controls and inspections. If the probability of failure is higher, it is more difficult to detect the degree of failure and the effect of the degree of failure is also more serious. In such cases, the degree of risk is also higher. Therefore, we can define the risk as Risk Priority Numbers (RPN) which takes the occurrence of failure modes (O), the severity of failures effect (S), and the probability of detection (D) into account as follows:

$$\mathrm{RPN} = \mathrm{O} \times \mathrm{S} \times \mathrm{D} \tag{1}$$

In the next step, the RPN is obtained from the product of these three parameters in order to measure the risk and severity of a failure mode. Hence, we can evaluate the three components of FMEA according to different natures of the green supply chain and can define four subcomponents: quality severity, time severity, elasticity severity, and cost severity. In addition, the degree of occurrence and difficulty of detection can also be expanded in different directions.

3.2. ANP Decision Process

Saaty [51] proposed the use of the Analytic Hierarchy Process (AHP) in solving different kinds of MCDM problems, including selection, sorting, and classification by the hierarchical structure. The process consists of three levels: goal, criteria, and alternatives. In the past, many researchers used the AHP or ANP methods to deal with real-world complicated decision-making problems. However, the ANP model does not require a strict hierarchical relationship as the AHP does, which makes it increasingly popular among decision-makers. Hsu et al. [57] proposed a hybrid ANP model as an improved method to evaluate multiple criteria and sub-criteria of e-service quality with the interdependence perspective. Lam and Dai [58] integrated the ANP with quality function deployment (QFD) to develop environmental sustainability performance. Chen et al. [59] used the ANP to construct a performance evaluation system for implementing green supply chains among enterprises. Giannakis et al. [60] developed a sustainability performance measurement framework for supplier evaluation and selection using the ANP method where the proposed evaluation system provided details on observing sustainable supply chain performance.

Wan et al. [61] adopted ANP and evidential reasoning methods to build a new sustainable supply chain management assessment model which includes innovation and value co-creation dimensions. The nodes in an AHP problem were compared in pairs where 1 meant that they are equally important and, at the other extreme, 9 meant that one node is more important than the other one. The result of the pairwise comparison was entered into a Comparison Matrix (**A**), and the relative importance of the node of one level in relation to a given node of the previous level was obtained as the principal eigenvector of a matrix. Thus, the relative importance of every element node of one level of the hierarchy (w) was obtained as follows:

$$\mathbf{A}\, w = \lambda_{\max}\, w \tag{2}$$

where $\mathbf{A}$ = comparison matrix; w = importance vector; $\lambda_{\max}$ = maximum eigenvalue of matrix $\mathbf{A}$.

Saaty [51] expressed the hierarchy and network structures as an ANP method to capture different aspects of tacit knowledge. Elements were grouped into clusters of related factors rather than hierarchical levels. Links were made from a parent factor in a cluster to several elements, and then efforts were made to overcome the disadvantage of traditional AHP [48,62]. The framework of the ANP is shown in Figure 2.

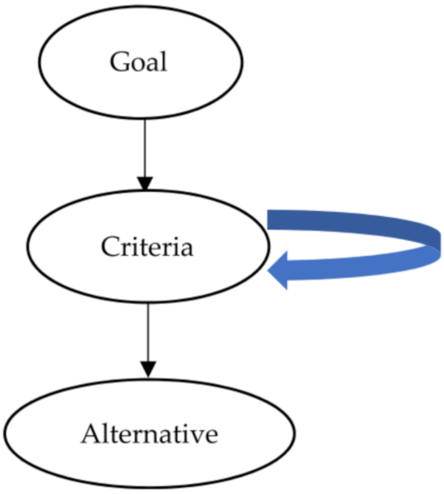

Figure 2. The framework of the ANP.

In the super-matrix $\mathbf{W}_{\mathrm{ANP}}$, $\mathbf{W}_{21}$ is a vector that represents the impact of the goal on the criteria and $\mathbf{W}_{32}$ is a vector which represents the impact of the criteria on each of the alternatives. The interdependency is expressed by the presence of matrix $\mathbf{W}_{22}$ in the (2, 2) entry of the super-matrix [51].

$$\mathbf{W_{ANP}} = \begin{bmatrix} 0 & 0 & 0 \\ \mathbf{W}_{21} & \mathbf{W}_{22} & 0 \\ 0 & \mathbf{W}_{32} & \mathbf{I} \end{bmatrix} \tag{3}$$

A network model is composed of nodes grouped into clusters according to a criterion depending on the problem to be addressed. In general, ANP can be described as follows:

Step 1: Represent the problem as a network;

Step 2: Perform a pairwise comparison from the nodes of each cluster in relation to any other node of the network. This procedure results in priority vectors;

Step 3: Input the priority vectors into a super-matrix;

Step 4: Power the super-matrix to obtain the limiting super-matrix. The resulting matrix contains the priority of every node within a cluster.

3.3. Grey Relational Analysis

Grey Relational Analysis (GRA) is used to explore the qualitative and quantitative relationships among abstract and complex sequences, and capture their dynamic characteristics during the development process. The interactions between economics, social responsibility and ecology involve multiple intricate objectives and factors. The calculation of GRA reveals the relationship between two discrete series in a grey space. According to the definition of grey system theory proposed by Deng [63], the grey relational grade must satisfy four axioms, including norm interval, duality symmetry, wholeness, and approachability. Therefore, let X be the grey relational set. $x_0 \in X$ is the reference series and $x_i \in X$ is the compared series. $x_0(k)$ and $x_i(k)$ are the values at a time or criterion k, $k = 1, 2, \ldots, n$. The grey relational degree between the two series at a time t is represented by the grey relational coefficient $r(x_0(k), x_i(k))$, which is defined as follows:

$$r(x_0(k), x_i(k)) = \frac{\min_i \min_k |x_0(k) - x_i(k)| + \xi \max_i \max_k |x_0(k) - x_i(k)|}{|x_0(k) - x_i(k)| + \xi \max_i \max_k |x_0(k) - x_i(k)|}, \quad k = 1, 2, \ldots, n; i = 1, 2, \ldots, m. \tag{4}$$

$\xi \in [0, 1]$ is a distinguishing coefficient for controlling the resolution scale, which usually assigns a value of 0.5. Therefore, when considering the unequal weights amongst the criteria, the grey relational degree of each comparison series x_i ($I = 1, 2, \ldots ., m$) to the reference series x_0 at all criteria can be expressed as follows:

$$r(x_0, x_i) = \sum_{k=1}^{n} w_k \times r(x_0(k), x_i(k)),\ i = 1, 2, \ldots, m. \tag{5}$$

If $r(x_0, x_i) > r(x_0, x_j)$, then the element series x_i is closer to the reference series x_0 compared to the series x_j. In this study, the weight (w_k, $\Sigma w_k = 1$) for each performance characteristic was computed by using the ANP method.

4. Results

The regulations of RoHS, WEEE, and Eup imply Extended Producer Responsibility (EPR), where manufacturers must ensure that the products obtained from raw materials, the manufacturing process, transportation to consumers, and recycling after a disposal will not pollute the environment. In Taiwan, laptop manufacturers play an important role, as they consider EPR from the design, the purchase of raw materials and components from the supplier, the manufacturing procedure, and the recycling of the waste laptop. This study selected a world-leading laptop manufacturer in Taiwan and used a focus group to interview senior managers and engineers from the company to define the risk criteria in each risk factor of the green supply chain and the RPN components and sub-components of FMEA. The in-depth interviews were conducted using the ANP questionnaire with eight senior experts who had been working with material suppliers for more than eight years. Three RPN components of FMEA with seven sub-components were defined under five green supply chain risk factors.

4.1. Confirm the Risk Factors

We reviewed the literature to identify green risk factors from the perspective of a closed-loop laptop supply chain. We then conducted a focus group in-depth interview with eight senior managers and engineers from a laptop manufacturing company in Taiwan. Based on these, we finally derived the risk criteria from five green risk factors defined below:

1. The risk criteria under the green design
    - Since the designed green products are too ideal, in the manufacturing stage it is difficult to always match the requirements;
    - Information platforms are not compatible with upstream and downstream vendors;
    - The market misunderstands green concepts and causes losses;
    - More environment-friendly materials are required as per rules which contradict the previous design concepts;
    - The improvements in green packaging design increase product costs;
    - The predicted sales for new products are incorrect and these increase expenditure.
2. The risk criteria under the green procurement
    - The purchased parts or raw materials suffer from toxic pollution;
    - The purchased materials do not meet the suppliers' requirements;
    - Green procurement begins with smaller bargaining with the suppliers;

- Replacement of dangerous/prohibited/restricted materials is not available;
- The inspection of the batch goods by the supplier is uncertificated;
- Customers' requirements do not comply with the specifications, thus causing obstacles to the transaction.

3. The risk criteria under the green manufacturing process
   - Facilities in the factory are not fully converted which contaminates the product during the manufacturing process;
   - The change in the manufacturing process increases the expenditure on hardware and software equipment;
   - Product inspections do not meet the green conditions required by the customer;
   - Factory spends a large amount to set up the green manufacturing process;
   - Quality control is not reliable in the green manufacturing process;
   - Energy damage and waste solvents increase during the green manufacturing process.
4. The risk criteria under green marketing
   - Most consumers do not have sufficient awareness of green products;
   - Sales of green products are less than the prediction;
   - Promotions of green products do not attract consumers significantly;
   - The unstable political situation in the world impacts the green supply chain;
   - Market preference for green products is lower;
   - Green regulations around the world increase trade restrictions.
5. The risk criteria under the green recovery
   - Recovery products are converted into secondary products which are then contaminated and scrapped;
   - Recovery products and parts are broken down in the disassembly process;
   - In the process of recycling the relevant personnel lack knowledge which causes defects in the recycling process;
   - Compare to new products it is difficult to promote refurbished products in the market without subsidies;
   - The recycling process and policies are not complete and so, most consumers find it difficult in joining recycling activities;
   - Recovery products are refurbished as secondary products which do not meet customer needs.

4.2. ANP Questionnaire Development

To assess the degree of risk for each criterion, we selected three senior quality directors, three procurement managers, and two senior engineers from the material supplier of the laptop manufacturing company to finish our ANP questionnaire. Based on the FMEA framework, the ANP questionnaire was designed to compare subcomponents of RPN in pairs. For each phase/factor of the green laptop supply chain, the relative importance of the subcomponent in each pair was weighted from 1 to 9, representing equal importance to extremely high importance over the other. Table 1 shows an example of a comparison between information difficulty and R&D difficulty under the predictable occurrence subcomponent in the green design factor.

Table 1. ANP questionnaire of information—R&D difficulty under predictable occurrence for green design factor.

	Green Design																	
	Under "Predictable Occurrence", Please Judge Which Subcomponent Is More Important.																	
Detection Subcomponent	**Extreme Important**			**Very Important**			**Moderate Important**		**Equal Important**	**Moderate Important**		**Very Important**			**Extreme Important**			**Detection Subcomponent**
Information difficulty	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	R&D difficulty

We assumed that each RPN subcomponent should have different expected importance based on the assessment of different experts. Next, as shown in Figure 3, we processed the ANP network hierarchy to obtain the weights of the subcomponents of RPN in green design with respect to RPN components of severity, occurrence, and detection in the FMEA.

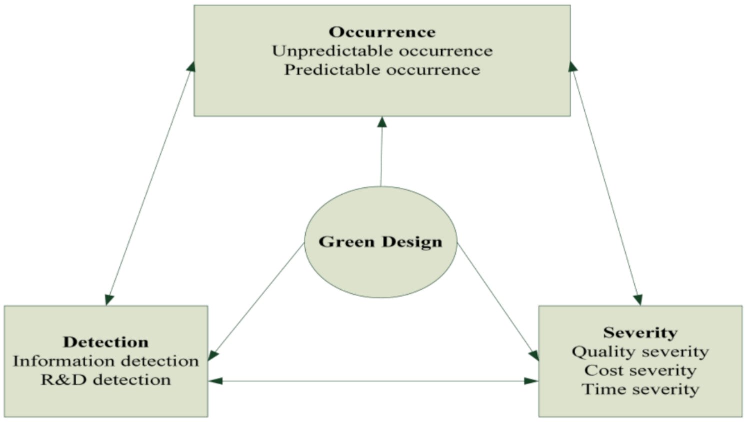

Figure 3. The ANP plot of green design.

4.3. The Weights of RPN Subcomponents

Therefore, by incorporating the evaluations by eight experts into the designed ANP as shown in Table 2, we obtained the weights of RPN subcomponents for the risk of green design. By the same process, running each green risk factor, we incorporated the evaluation made by the experts into the Super Decision software based on the designed network relationship among the RPN subcomponents. Finally, the weight of the RPN subcomponent under the corresponding green factors was obtained as shown in Table 3.

Table 2. The weights for each RPN subcomponent.

Risk Factors	RPN Components	RPN Subcomponents	Weight
Green design	Severity	Quality severity	0.15
		Cost severity	0.03
		Time severity	0.01
	Occurrence	Unpredictable occurrence	0.27
		Predictable occurrence	0.19
	Detection	Information difficulty	0.16
		R & D difficulty	0.19

Table 3. The weights for each RPN subcomponent.

Risk Factors	RPN Components	RPN Subcomponents	Weight
Green procurement	Severity	Quality severity	0.19
		Cost severity	0.14
		Time severity	0.10
	Occurrence	Low improvement performance	0.16
		High improvement performance	0.07

Table 3. *Cont.*

Risk Factors	RPN Components	RPN Subcomponents	Weight
	Detection	Technical difficulty	0.20
		Performance difficulty	0.14
Green manufacturing process	Severity	Quality severity	0.22
		Cost severity	0.09
		Time severity	0.11
	Occurrence	High incidence of prevention	0.06
		Low incidence of prevention	0.23
	Detection	Self-assessment difficulty	0.11
		High incidence of prevention	0.18
Green marketing	Severity	Brand image severity	0.20
		Cost severity	0.06
		Sales severity	0.19
	Occurrence	High involvement	0.10
		Low involvement	0.13
	Detection	Difficulty in enterprise decision making	0.16
		Environmental difficulty	0.16
Green recovery	Severity	Quality severity	0.09
		Cost severity	0.14
		Brand image severity	0.16
	Occurrence	Exogenous occurrence	0.17
		Self-generating degree	0.14
	Detection	Heavy industry difficulty	0.19
		Verify difficulty	0.11

4.4. Ranking the GRA Coefficient for Each Green Risk Criteria

To rank the risk criteria in each risk factor, we first evaluated the relationship between the criteria of green design and RPN components as shown in Table 4 by asking the eight experts to what extent the criteria of green design and RPN components are correlated (1 = the least strongly, 100 = the most strongly), and then we derived the GRA coefficient for each criterion as shown in Table 5, which shows the importance of risk criteria in green design.

Table 4. The collected data between green design and RPN components.

RPN Components	Occurrence		Detection		Severity		
Subcomponents Green Criteria	**Unpredictable Occurrence**	**Predictable Occurrence**	**Information Difficulty**	**R & D Difficulty**	**Quality Severity**	**Time Severity**	**Cost Severity**
Information platforms are not compatible with upstream and downstream vendors	57	67	55	42	57	52	55

Table 4. *Cont.*

RPN Components	Occurrence		Detection		Severity		
Subcomponents Green Criteria	**Unpredictable Occurrence**	**Predictable Occurrence**	**Information Difficulty**	**R & D Difficulty**	**Quality Severity**	**Time Severity**	**Cost Severity**
The designed green products are too ideal; the manufacturing stage is difficult to match the requirements.	64	62	51	58	57	65	61
The market misunderstands green concepts and causes losses	59	51	40	64	40	57	61
More environmentally friendly materials are required from rules which conflict with previous design concepts	40	51	48	51	45	61	66
The improvements in green packaging design lead to the increased product cost.	45	50	67	40	52	59	67
The predicted sales for new products are incorrect and make the expenditure increase.	59	59	52	59	34	40	43

Table 5. The ranking of the green criteria in the green design.

Risk Criteria	GRA Coefficient	Ranking
Since the designed green products are too ideal, in the manufacturing stage it is difficult to always match the requirements	0.775863	1
Information platforms are not compatible with upstream and downstream vendors	0.513431	5
The market misunderstands green concepts and causes losses	0.497567	6
More environment-friendly materials are required as per rules which contradict previous design concepts	0.551761	4
The improvements in green packaging design increase product costs.	0.701096	2
The predicted sales for new products are incorrect and these increase expenditure.	0.560224	3

The criterion "since the designed green products are too ideal, in the manufacturing stage it is difficult to always match the requirements" is the most important risk criterion in green design. Therefore, if green innovation is embedded in a designed product, all elements from functionality, production, assembly, testing, maintenance, environmental impact, and disposal and recycling should be taken into consideration in the early design phase. The second important criterion is "The improvements in green packaging design increase product costs." In the early stage, the overall recycling rate of laptop packaging (including cartons and plastic components such as fillers and tape) is less than half and sometimes almost zero. To achieve environmental sustainability and comply with environmental regulations, most manufacturers need to improve packaging design, reduce the impact of packaging materials on the environment, reduce packaging, optimise volume utilization design, and simplify packaging design, thus increasing the packaging cost. In green procurement, as shown in Table 6, the risk criterion of "the purchased parts or raw materials suffer from toxic pollution" is the most important.

Table 6. The ranking of the green criteria in green procurement.

Risk Criteria	GRA Coefficient	Ranking
The purchased parts or raw materials suffer from toxic pollution.	0.724066	1
The purchased materials do not meet the suppliers' requirements.	0.575969	5
Green procurement begins with smaller bargaining with the suppliers.	0.564806	6
Replacement of dangerous/prohibited/restricted materials is not available.	0.645363	4
The inspection of the batch goods by the supplier is uncertificated.	0.649732	3
Customers' requirements do not comply with the specifications, thus causing obstacles to the transaction.	0.668564	2

In one famous case, Sony, which had delivered a batch of 2.5 million PS2s in October 2001, was fined 17 million Euros because the Cadmium exceeded the Dutch government's regulations. Therefore, manufacturers are expected to build close relationships with material suppliers to avoid toxic materials in their products. The second most important criterion is "customers' requirements do not comply with the specifications, thus causing obstacles to the transaction." For environmental sustainability, designers are in a dilemma because some parts in the shell of a laptop are biodegradable, which makes customers feel that the quality is not up to their expectations. By the same process, we can obtain the other ranking criteria for the risk factor from Tables 7–9, including the green manufacturing process, green marketing, and green recovery, respectively. Therefore, the laptop manufacturer can apply the research results to revise the possible green risks in order to make continuous improvements in their green activities.

Table 7. The ranking of the green criteria in the green manufacturing process.

Risk Criteria	GRA Coefficient	Ranking
Facilities in the factory are not fully converted which contaminates the product during the manufacturing process.	0.713383	2
The change in the manufacturing process increases the expenditure on hardware and software equipment.	0.579363	5
Product inspections do not meet the green conditions required by the customer.	0.616764	6
Factory spends a big amount to set up the green manufacturing process.	0.668709	3
Quality control is not reliable in the green manufacturing process.	0.616710	5
Energy damage and waste solvents increase during the green manufacturing process.	0.721563	1

Table 8. The ranking of the green criteria in the green marketing.

Risk Criteria	GRA Coefficient	Ranking
Most consumers do not have sufficient awareness of green products.	0.761535	1
Sales of green products are less than the prediction.	0.558531	6
Promotions of green products do not attract consumers significantly.	0.573201	5
The unstable political situation in the world impacts the green supply chain.	0.641613	2
Market preference for green products is lower.	0.597132	4
Green regulations around the world increase trade restrictions	0.639353	3

Table 9. The ranking of the green criteria in the green recovery.

Risk Criteria	GRA Coefficient	Ranking
Recovery products are converted into secondary products which are then contaminated and scrapped.	0.744296	1
Recovery products and parts are broken down in the disassembly process.	0.514657	6
In the process of recycling the relevant personnel lack knowledge which causes defects in the recycling process.	0.621132	3
Compare to new products it is difficult to promote refurbished products in the market without subsidies.	0.598816	4
The recycling process and policies are not complete and so, most consumers find it difficult in joining recycling activities.	0.585907	5
Recovery products are refurbished as secondary products which do not meet customer needs.	0.703038	2

Components of a laptop include mainboards, memory, chips, etc. Due to new environmental regulations such as WEEE and RoHS directives, laptop manufacturers are bound to change their product design, procurement, production, marketing, and recycling processes. Therefore, most laptop manufacturers, due to their technology and their dominant interest in controlling costs, cannot fully understand the substitute materials, which causes uncertainty. Besides, these manufacturers cannot ensure that the quality of their products always meets customers' requirements. Quality control of components becomes difficult. Defects in the recycling process also lead to ineffective recycling. Therefore, uncertainty in green risk factors becomes a major concern for this industry. However, on the premise of activity-based classification, concentrating resources on key risks is more practical. Hence, after ranking the risk criteria for each green risk factor, as shown in Table 10, we listed the first two criteria in each green risk factor to develop a checklist for continuous improvement in green activities. The summed weights of the top 2 criteria comprise more than 40% of total GRA coefficients in their corresponding risk factors. It also appears that a prioritized criterion has a GRA coefficient of 0.7 or a portion of its GRA coefficient to the total risk factor is over 0.17. For strategizing the timeframes of a continuous improvement process, we found these prioritized risk criteria to be able to be addressed in the short term, and that the rest of the criteria can be successively integrated with the next timeframe since all 30 criteria from the six risk factors were found to be significantly vigilant by the domain experts.

Table 10. The prioritized criteria for improvement works in each green risk.

Green Factors	Prioritized Criteria for Improvement
Green design	• Since the designed green products are too ideal, in the manufacturing stage it is difficult to always match the requirements. (0.775863) • The improvements in green packaging design increase product costs. (0.701096)
Green procurement	• The purchased parts or raw materials suffer from toxic pollution. (0.724066) • Customers' requirements do not comply with the specifications, thus causing obstacles to the transaction. (0.668564)
Green manufacturing process	• Energy damage and waste solvents increase during the green manufacturing process. (0.721563) • Facilities in the factory are not fully converted which contaminates the product during the manufacturing process. (0.713383)
Green marketing	• Most consumers do not have sufficient awareness of green products. (0.761535) • The unstable political situation in the world impacts the green supply chain. (0.641613)
Green recovery	• Recovery products are converted into secondary products which are then contaminated and scrapped. (0.744296) • Recovery products are refurbished as secondary products which do not meet customer needs. (0.703038)

Remark: values in ( ) are the GRA coefficients.

The risk assessment model proposed in this study allows manufacturers to find out the risks they are likely to face during product design, procurement, manufacturing, marketing, and recycling based on the environment. According to the risk assessment process followed in this research, the relative GRA value can be calculated to assist manufacturers and their suppliers to find out the ranking of risk criteria in each green risk factor and prioritize modification plans for risk activities.

5. Conclusions

To build a sustainable environment, most manufacturers incorporate the green concept into their supply chain management. We found that, in addition to carefully measuring the existing resources, many risk criteria under each green risk factor must also be considered by the manufacturers in order to discover the issues that are to be dealt with while taking the most appropriate measures to minimize the loss and create more value for them. In this research, we focused on the process of the green supply chain and identified five factors of green risks. These are risks associated with green design, green procurement, green manufacturing, green marketing, and green recycling. Secondly, in this study, we expanded the RPN components of FMEA, including occurrence, detection, and severity, into subcomponents concerning the green risk factors, calculated the relative weights of the RPN subcomponents under each green risk factor using the ANP method, and, finally, combined those weights to obtain GRA coefficients to rank the important risk criteria in each green risk factor under the green supply chain.

The FMEA-ANP-GRA approach provided us with a procedure of risk identification and assessment throughout the closed-looped supply chain which can be used as a roadmap for other industries as well. In the case of laptop manufacturers, the top two prioritized risks in each factor/ phase were found to be complying with the Preto principle as the "vital few" and deliberately selecting to formulate important prevention strategies from respective risk sources. Therefore, a higher performance of green supply chains can be attributed to a higher efficiency of risk harness measures. Of the 10 risks selected in this study, 4 are customer-oriented risks and can be used to identify the highest priority that should be tackled in the interest of green risk management. This includes the two criteria: "since the designed green products are too ideal, in the manufacturing stage it is difficult to always match the requirements (GRA coefficient = 0.775863)" and "most consumers do not have sufficient awareness of green products (GRA coefficient = 0.761535)."

Our findings emphasized the significance of an external infrastructure and process that sufficiently integrates enterprises with customers (and other stakeholders) and maximizes the external sources of publicity by forging a long-term relationship with customers. To capture customer attachment, likingness, and feedback toward green products, a formal sentiment-tracking mechanism is needed to monitor and analyze customer satisfaction as well as any potential needs. Collaboration with customers can escalate the efficiency and effectiveness of green supply chain management by taking timely preventive actions from detecting and preventing possible failures in green design, green procurement, green manufacturing process, green marketing, and green recovery.

To recapitulate, a laptop manufacturer can apply the checklist that we developed to make continuous improvements in their green activities. Most importantly, based on this proposed risk analysis procedure, the manufacturer can not only comply successfully with international regulations related to environments but can also help in building a brand image through customers' word of mouth.

Limitations and Future Research

Since our research focused on a laptop manufacturer in Taiwan and their suppliers, we interviewed a sample of personnel from different types of companies including manufacturers and suppliers as well as those from OEM/ODM companies. In the case analysis of our study, we conducted in-depth interviews with the heads of the companies responsible for the green supply chain in the sample company. However, we understand that the risk factors are likely to be different from others because of the company's own business environment. While this study is based purely on the basis of discussions that we had with personnel from the sample company, it is highly likely that, if other types of manufacturers in other product segments are taken into consideration in future studies, there may be more effective ways of defining green risks. In addition, we used the FMEA-ANP-GRA in this study to create a framework for risk analysis in the green supply chain which can be used to a limited extent for continuous improvements in laptop manufacturing only. Since the risk factors may differ depending on different industries in future research, a comprehensive decision analysis procedure can be built by incorporating criteria weights from more experts' subjective and objective views to enhance the extent to which the risk factors from the literature can be identified and defined. We also suggest that, in the future, researchers can create a fuzzy model to deal with experts' linguistic expressions, especially with the help of the Fuzzy-FMEA-ANP-GRA model for risk analysis.

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