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Risk Management of Hazardous Substances in Selection of Green Suppliers

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In order to satisfy customer requirements to comply with the control of hazardous substances (HS), most suppliers have developed a twofold strategy comprising certified document review and online testing. Nevertheless, many suppliers remain far from complying, collecting, and managing such data efficiently. They encounter significant challenges and risks in screening all the hazardous substance contained in received components as part of the green part approval management (GPAM) process. The present study developed a failure mode and effects analysis (FMEA) for component risk, based on component types. In addition, suppliers' HS control performance is further evaluated, based on FMEA and X-bar control chart. The results indicate the risk level for each supplier. Finally, the proposed FMEA model is applied to a case study of an electronics supplier.

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1. Introduction

The Europe Union (EU) issued the Restriction of the Use of Certain Hazardous Substance (RoHS)[1] Directive and the Registration, Evaluation and Authorization of Chemicals (REACH)[2] Regulation in 2003 and 2009, respectively. The purpose of these two pieces of legislation is to ban or control hazardous substances (HS) used in products. It could been seen as part of green manufacturing.[3,4] In response to RoHS and REACH, electrical and electronics enterprises such as Dell, HP, IBM, Motorola, Sony, Panasonic, NEC, Toshiba, and Samsung began to adopt green supply chain systems (GSCS). These enterprises required their upstream suppliers to provide non-hazardous parts/components for green procurement based on IECQ QC080000 HSPM.[5] For example, Sony initiated Green Partner Activities and required all of its suppliers to review and strengthen their environmental management efforts.[6] It issued Green Partner certification to its business partners to ensure that all components complied with its green procurement guide, SS-00259. The goal was to ban or phase out the use of controlled substances in the design, manufacture, and distribution of products. Meanwhile, Samsung developed the ECO partner[7] program for its suppliers. Samsung has employed an Eco-partner policy since May 2004. In order to manage hazardous substances in components, it provides an environmental quality management system of cooperating companies and performs audits of its suppliers.

In order to satisfy the requirements of these original brand manufacturers (OBMs) to comply with the control of HS, their suppliers—most of which are original design manufacturers (ODMs) and original equipment manufacturers (OEMs)—have developed a twofold strategy: certified document review and online testing. The first stage involves requiring suppliers to submit part/component testing reports to improve risk control. The second stage is to screen the part/component using analytical instruments such as X-ray fluorescence (XRF) spectrometers during the incoming quality control (IQC) stage. Thus, suppliers face the difficulty of obtaining detailed information for thousands of parts from suppliers across the world. Generally, a product will be dissembled according to the rule of 'homogeneous material' to evaluate its HS based on the bill of materials (BOMs). For example, a product with 500 parts, 72,000 (= 500 × 3 × 2 × 4 × 6) testing certificates need to be checked and verified according to the European Information and Communications Technology Industry Association[8] (Figure 1). Furthermore, for every testing report, many checkpoints need to be verified, such as the date, the testing portion, the testing chemical, the tested thresholds, and so on. Despite committing significant resources to such procedures, suppliers are still far from complying, collecting, and managing such data efficiently.[9] They encounter significant

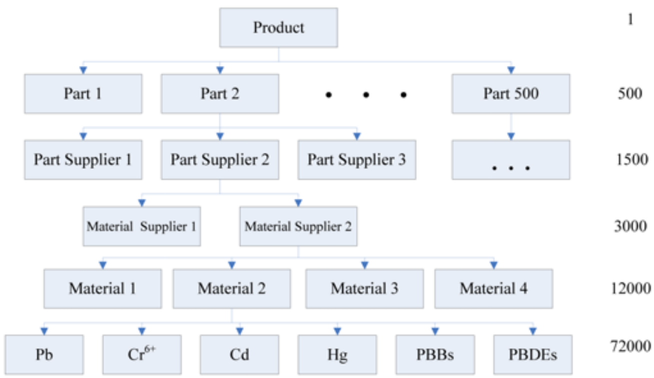

Fig. 1 There will be 72,000 certificates for a product with 500 parts[6]

challenges and risks in screening all the hazardous substances contained within received parts/components during the green part approval management (GPAM) process.

Currently, some enterprises have already introduced an information system to control and monitor their components in an attempt to comply with the regulations; however, green supply chain managers are still managing associated risks, for reasons summarized as follows:

(1) Product research and development (R&D) cycles are short; component information therefore changes rapidly, reducing the validity of static content.

(2) Vague Directives provide no clear insight on the depth of information needed to acceptably mitigate risk.

(3) OBMs will ask their suppliers to respond to surveys on parts/components content. However, due to short timeframes, suppliers' responses are too frequently erroneous (and possibly fraudulent).

(4) The most critical reason is the inconsistent test requirements for the job shop information and document verification. Most parts/components are still contained HS even though their accompanying testing report was passed and certified.

Most recent literatures[10-12] on environmental management indicate that risk management has a critical issue, especially in green supplier selection. The present study develops a Failure mode and effects analysis (FMEA) of components, based on the risks associated with differing material types. In addition, suppliers' HS control performance is further evaluated based on the FMEA method and X-bar control chart. The results indicate the level of risk for each supplier. Finally, the model is used to examine a real supplier FMEA case.

The remainder of the paper is structured as follows: Section 2 reviews the relevant literature; Section 3 details the methodology; Section 4 presents a description, evaluation, and analysis of the two business models; and lastly, Section 5 offers a discussion on the research findings.

2. Literature Review

2.1 Impacts of RoHS and REACH directives

The RoHS Directive mainly regulates six chemical substances in electrical and electronic products: Pb, Cd, Hg, Cr + 6, PBBS, and PBDEs. The industries that may be impacted by RoHS include IC (integrated circuit), PCB (printed circuit board), notebook computers, desktop computer, LCD technologies, semiconductors, mobile phones, communication devices, data exchangers, and medical appliance industries. The EU REACH program regulates highly toxic or hazardous chemical substances that are widely used. Among more than 30,000 chemical substances, 1,400 toxic or hazardous substances are termed substances of very high concern (SVHC). SVHC refers to substances that have been scientifically demonstrated to cause probable serious damage to human health and the environment, and are categorized as: CMR, PBT, and vPvB. Within the electronics industry, 15 kinds of chemical substances are regulated by REACH, within three categories: halogen compounds, arsenic compounds, and non-used or limited/prohibited chemical substances.

2.2 Hazardous substance control management

Recently, large electronics firms have pressured their suppliers to achieve environmental performance targets, increasing the motivation for cooperation between suppliers and customers to achieve environmental objectives. To reduce the hazardous material risk, Evans and Johnson emphasized that a testing plan should be developed, based on the presence of high-risk components.[13] Eveloy et al.[14] also mentioned that conducting chemical analysis of procured materials, parts, and subassemblies may be necessary to ensure compliance with legislative requirements for the upstream suppliers. They suggested that portable XRF spectrometers may be used to analyze a wide variety of product materials, and that XRF analysis is considered the best solution for rapid, non-destructive screening of parts or components.[15] Ninagawa et al.[16] argued that quality assurance staff should check components using an analytical instrument, but this process entails a large number of person-hours in the analysis of all purchased components. Gong and Chen[17] also proposed several critical control processes from a systematic point of view, to fulfill environmental requirements at the product development stage. Wang and Kuo[18] proposed using AHP and FMEA to produce a selection hierarchy based on risk analysis, for use in selecting green vendors. In their study, the Disassembly Effort Index (DEI), Input Quality Control (IQC), Logistics, and Vendor Management are represented as the risk utility function. Hsu and Hu[19] proposed an HSM-based supplier selection model that used the ANP methodology to recognize the criteria.

In terms of cost and efficiency, original assembly manufacturers may suffer from inspecting hundreds or thousands of green components via an analytical instrument. Regardless of the importance of green components in meeting growing worldwide environmental regulations on the restriction of hazardous substances, it appears that there is an urgent need for manufacturers to develop a risk assessment framework in order to systematically manage suppliers of green components. In this study, we propose an assessment framework to identify high-risk green components. To our knowledge, most of the previous literature[20,21] on supplier selection is limited to exploring the criteria of cost, quality, and delivery time. Few previous studies have focused on supplier selection and risk that considered the hazardous substance (HS).

2.3 Failure mode and effects analysis

FMEA is an inductive procedure that moves from the specific to the

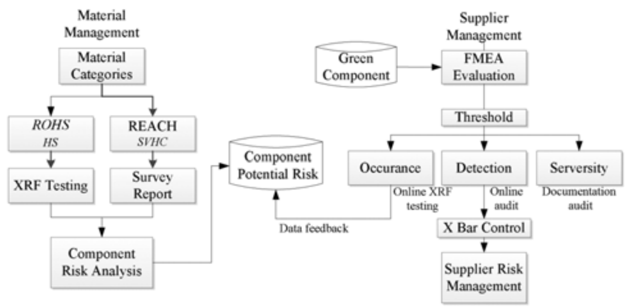

Fig. 2 FMEA model for risk analysis of components and suppliers

general. Chin et al.[22] defined a failure mode as the manner in which a component, subsystem, system, process, etc. could potentially fail to meet the design intent. Chin et al. also defined a failure effect as the result of a failure mode on the function of the product or process, as perceived by the customer. Stamatis[23] documented the detailed procedures involved in an FMEA in various applications within different industries. Liu et al.[24] reviewed evaluation approaches employed in failure mode and effects analysis. In this paper, the author collected and categorized many methods that are integrated with FMEA.

3. Research Method

This study analyzed the risks of hazardous substances contained within electronic components according to the material characteristics and environmental protection performance of component suppliers, in order to establish a material control and management system. The model assessed supplier risk via FMEA, while material risk was evaluated according to the characteristics of materials regulated by RoHS and REACH. In Figure 2, the risk of component is evaluated based on the test report of RoHS and REACH. Then the suppliers are evaluated based on the FMEA method. And it comes out a supplier risk management system.

3.1 Component risk analysis

Certain components may contain particular hazardous materials; thus, enterprises may request their suppliers to provide samples and conduct XRF testing when replenishing stock. Many studies have demonstrated that XRF is an effective selection instrument; however, due to hardware and technical limitations, only total chromium or total bromine content can be tested, and this cannot replace traditional chemical analysis. In consideration of time, labor, cost, confidence, and convenience, XRF is an effective analysis instrument. In this study, a twofold strategy is developed, based on analysis of HS and SVHC.

3.1.1 The HS evaluation in RoHS directive

In order to control the HS, some XRF results are collected and analyzed. Since XRF includes a precision error, we used a threshold of 0.75 as the XRF prioritization criterion, and specified the criteria for XRF testing, as shown in Table 1. The values were assigned to categories A - D, according to RoHS thresholds, and prioritized concentration risks measured by XRF instruments. For each material,

Table 1 XRF prioritization criterion[14]

Level	Risk	Weigh-ting	Cd	Pb, Hg, Cr + 6, PBBs, PBDEs, Br, Cl
EU threshold			100	1000
Level A (0 ~ 25%)	Low	w_j	25	0~250
Level B (25% ~ 75%)	Medium		25~75	250~750
Level C (75% ~ 100%)	High		75~100	750~1000
Level D (> 100%)	Very High		>100	>1000

Table 2 Binominal distribution for testing XRF values (unit ppm)

Part	Testing item mg/kg	Pb	Cd	Hg	Cr + 6	PBBs/ PBDEs	Pass/ Failed
	MDL	2	5	2	2	2	
1	Metal	279,669	Nd	Nd	Nd	Nd	Failed
2	Plastic	Nd	14	Nd	Nd	562	Failed
3	Metal	870	250	Nd	Nd	Nd	Failed
			…				
i	Plastic	Nd	Nd	Nd	Nd	Nd	Pass

*MDL: method detection limit
Nd.: not detected

the material/component potential risk is calculated as a potential risk value (PRV).

$$PRV_i = \Sigma w_j P(\%)$$

where
i denotes the material/component
j denotes level A - D
w_j denotes the weighting for level *j, 1,3,9,and 27*

3.1.2 SVHC in REACH

REACH directive regulates 15 SVHCs, and determines whether the final products contain levels of SVHC that exceed limits of 0.1%. If the finished products contain SVHCs, the information should be disclosed. If the SVHCs exceed the 0.1% limit, buyers should be notified, and the products can be used after authorization. From industry experience, it requires significant resources (financial and human resources) to test the potential risk of materials/components based on the requirement of REACH. Therefore, a survey form was developed and distributed to suppliers.

3.2 Supplier management

In HS control flow, due to the numerous documents involved, many manufacturers have established and modified their systems and workflows to construct green databases and information platforms for document control. Enterprises generally require their suppliers to provide statements or declarations, testing reports, or material certificates through the procurement system, in order to demonstrate that their supplied components meet the required specifications. Enterprises also conduct audit management and material tests to confirm that their suppliers meet the specifications.

As enterprises have established information systems and collected large sets of supplier data, the binominal distribution is applied to test the report data. In Table 2, it means once if anyone of the six HS materials are contained than the threshold, it is failed. It is worth noting that different components with different combinations of materials should be disassembled to the level of homogeneous materials for the testing report. The same method is also applied to the XRF analysis.

In addition, in order to make sure it is in control, the EU threshold limit is used. This study used historical performance of suppliers and the upper control limit (UCL) and lower control limit (LCL) of the control diagram to find the undesirable upper control limit and average value of the X-bar control diagram. Dynamic risk was calculated as follows:

$$UCL = p+3\sqrt{\frac{p(1-p)}{n}}$$

$$UCL = p-3\sqrt{\frac{p(1-p)}{n}}$$

where

p denotes average value of defect rate

n denotes testing number

The risk priority number (RPN) of the FMEA is then used to indicate the documents and information supplied by the suppliers, including occurrence probability, detection difficulty, and severity.

(1) Detection difficulty (D) is defined by the status in the testing report of the manufacturer. According to the RoHS requirements, manufacturers conduct overall investigation of product components, materials, and process; and further demand upstream suppliers to provide relevant documents, such as BOM, statement of non-use of hazardous substances, material statement, testing report, and material content declaration (MCD). The testing report is issued by a third-party laboratory, which decomposes the product supplied by the manufacturers into uniform materials; the cost is approximately NTD (New Taiwan Dollars)1,500~4,000 per test. The cost for testing the 15 items to REACH specifications is more than NTD 20,000. Thus, testing costs are the main concern for manufacturers. This study summarized and classified the materials listed in RoHS and REACH.
(2) Occurrence probability (O) is evaluated using the results from the material risk laboratory. As mentioned previously, the XRF testing results will be used for the evaluation.
(3) Severity (S) is defined as supplier audit documents; integrate. In recent years, many international manufacturers have established their own hazardous substances specifications, such as Sony's SS-00259, IBM-46G3772, Dell-6T198 and HP-00011-01. International manufacturers request their suppliers not to supply products that contain substances listed in the specifications. If the suppliers fail to comply with the specifications, besides taking social responsibility, they will receive a penalty, or may even have their supplier qualification revoked. In contrast, if suppliers can meet customers' needs and comply with the specifications by changing their materials or processes according to the product requirements, they will receive more orders, maintain market share, and enhance customer loyalty. To ensure that the suppliers meet the specifications, many manufacturers regularly conduct site audits of product quality of their suppliers. Manufacturers conduct audits in order to evaluate the ability of suppliers to manage their operations, to record deficiencies, and evaluate the performance of their suppliers. The audit process involves financial and staffing costs, but can significantly reduce supplier material risk.

Table 3 FMEA value

Risk level	S_j, O_j, D_j	
High	> UCL	9
Medium	LCL <= <= UCL	3
Low	Threshold < LCL	1
Threshold	< Threshold	0

Based on the three factors of Severity, Occurrence, and Detection, the RPN of supplier is evaluated if it is over the risk threshold. The RPN equation for each component/material is as follows. Table 3 shows the FMEA value.

$$RPN_j = S_j \times O_j \times D_j$$

where

S_j: severity of component / material j

O_j: occurrence probability of component/material j

D_j: detection difficulty of component/material j

4. Case study and analysis

In this study, a Taiwan electronic manufacturer is investigated. Due to confidential problem, the name is omitted. For incoming quality control, the company conducted sampling inspection and obtained 303 XRF tests. In addition, it collected data from 272 suppliers through the information system, and checked 8893 RoHS data and 1996 REACH data. The documents originate from (1) the chemical substance testing report of a third-party laboratory that complies with ISO 17025; (2) material content declarations; (3) substance safety data sheets; (4) compliance statements or certificates. The information provided by the suppliers was examined. The company used various relevant specifications for different product materials, audited whether the products met the specified limits, and rejected nonconforming products.

4.1 Component risk evaluation

In this research, 303 XRF reports across different material/ component categories are collected. For example, based on Table 2, Part 1 is made of metal, which tested a Pb value of 279,669 ppm, which is therefore within level D. Part 2 is made of plastics, which showed 562 ppm PBBs/PBDEs (level B), and does not exceed the threshold. The Pb and Cd contents of Part 3 are 870 and 250 ppm, respectively (level C). The XRF data in Table 3 indicate that lead (Pb) is the metal that most commonly exceeds the specified limit. Hence, lead is listed as the key substance to be tested by suppliers during supplier evaluation.

Table 4 shows statistics for the XRF test values of the 303 parts. The results show that items of different materials may contain highly hazardous substances. For example, lead is the metal that may easily exceed the limit as specified.

Table 4 Potential HS within components according to XRF

Category	*Cl*	*Pb*	*Cd*	*Hg*	*Cr*	*Br*
Metal	1%	15%	1%	0%	2%	0%
Connector	0%	38%	25%	0%	13%	13%
Plastic	31%	0%	0%	0%	0%	44%
Resistor/Capacitor	23%	0%	0%	0%	0%	23%
Cable	38%	0%	13%	0%	0%	0%
PCB	36%	1%	1%	0%	0%	52%

Table 5 Risk level for different components

Categories	No.	A	B	C	D	PRV	Rank
		No. (%)					
PCB	114	34(30)	1(1)	8(7)	71(62)	17.7	1
Cable	106	24(23)	12(11)	8(8)	62(58)	17.04	2
Connector	8	1(13)	3(38)	0(0)	4(50)	14.75	3
Plastics	13	6(46)	1(8)	0(0)	6(46)	13.15	4
Resistor/ Capacitor	54	24(44)	9(17)	2(4)	19(35)	10.78	5
Metals	8	5(63)	0(0)	0(0)	3(38)	10.75	6

Table 6 Potential substances within components

REACH	Potential SVHC	RoHS	Potential HS
Metal	~	Metal	*Pb*
		Connector	*Pb, Cd, Cr, Br*
Plastic	*DEHP (43%)* *DBP (14%),* *BBP (13%)* *HBCDD (9%)* *Alkanes C10-13 (5%)*	Plastic	*Cl, Br*
		PCB	*Cl, Br*
		Cable	*Cd, Cl*
Glass	*Diarsenic trioxide (16%)*	Resistor	*Cl, Br*
Ink and painting		Ink and painting	*Pb*

In Table 5, the highest PRV $(17.7 = 1 \times 0.3 + 3 \times 0.01 + 9 \times 0.07 + 27 \times 0.62)$ is the category of PCB, followed by 17.04 for Cables. Thus, supplier risk must be controlled through audits and document management when selecting a plastics manufacturer that tested higher than RoHS values, or else the risk to the enterprise will be increased.

Based on the 1996 REACH survey forms, the present study found that metal suppliers account for 24%, glass suppliers account for 66%, plastic suppliers account for 9%, and ink suppliers account for 1% of materials used by the case study company. The results showed that 101 test results (5%) indicated the presence of hazardous substances regulated by REACH, and 1895 (95%) data indicated no hazardous substances. The results were then compared with RoHS and REACH, as shown in Table 6. The data show that plastic, ink, and paint are of potential concern, as they contain HS and SVHC. Table 6 also shows that most of the plastics that contained HS and SVHC were PVC.

4.2 The risk of presented by suppliers

Based on the historical performance of the suppliers, the case company used test difficulty, occurrence probability, and severity to conduct risk evaluation. In order to get the normal distribution result, the threshold values used in detection, severity, and occurrence are shown in Table 7. The thresholds of the three factors, detection, severity, and occurrence, are 0.3, 680, and 0.1 respectively.

Table 7 Risk threshold values

	Detection	Severity	Occurrence
Threshold	0.3	680	0.1
Average	61	566.78	31.45
UCL	64.74	600	34.97
LCL	58.21	500	27.93

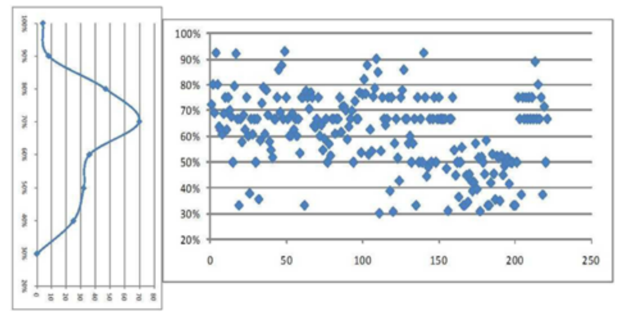

Fig. 3 Control diagram of detection for each supplier

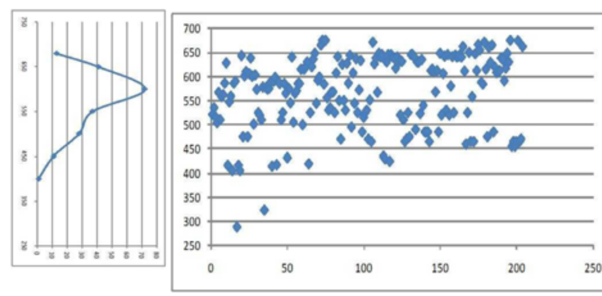

Fig. 4 Control diagram of severity for each supplier

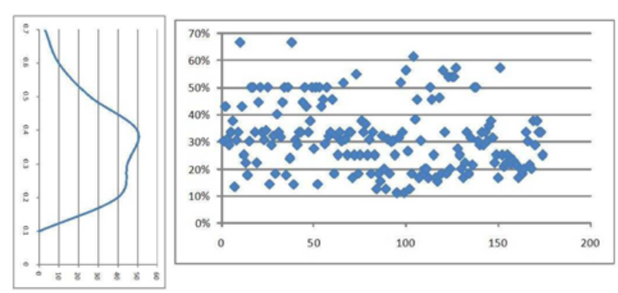

Fig. 5 Control diagram of occurrence for each supplier

4.2.1 Detection

This study found risks associated with the document management process. Figure 3 shows that the control diagram is concentrated on the upper and lower control limits, namely high risk and low risk. In the system preparation, the tested values of the substances are filled in according to the hazardous substances specification of the client. If the testing report cannot meet the specifications, a product qualification certificate cannot be obtained, and the material numbers are not listed in the BOM for purchase. For the enterprises, lower document management risk leads to better document management.

To avoid noncompliance, the suppliers' perception of the specifications and judgment of the values in the testing report should be enhanced, including testing methods, a limit on the detection values, and concentration.

Table 8 The highest risk supplier that RPN = 729

Component Category	Supplier	Failed %	D	Audit score	S	Failed %	O	RPN
Connector	14	67%	9	406	9	50%	9	729
PCB	93	75%	9	420	9	45%	9	729
Plastic	116	75%	9	417	9	43%	9	729
PCB	220	67%	9	485	9	54%	9	729
PCB	23	67%	9	485	9	54%	9	729
Cable	66	67%	9	465	9	38%	9	729

Table 9 Risk evaluation of 272 suppliers

RPN	Cable		Connector		IC		Metal		PCB		Plastic		Capacitor		Total	
	no	%	no	%	no	%	no	%	no	%	no	%	no	%	no	%
1	0	0%	0	0%	4	36%	1	9%	0	0%	1	3%	12	8%	18	7%
3	0	0%	0	0%	5	45%	1	9%	2	6%	1	3%	35	23%	44	16%
9	2	25%	2	10%	2	18%	2	18%	4	11%	5	16%	36	23%	53	19%
27	1	13%	7	33%	0	0%	1	9%	12	33%	6	19%	45	29%	72	26%
81	3	38%	9	43%	0	0%	2	18%	12	33%	12	39%	19	12%	57	21%
243	1	13%	2	10%	0	0%	4	36%	3	8%	5	16%	4	3%	19	7%
729	1	13%	1	5%	0	0%	0	0%	3	8%	1	3%	3	2%	9	3%
Total	8		21		11		11		36		31		154		272	

4.2.2 Severity

Severity (S) is defined using supplier audit documents. Many international manufacturers have released their own specifications and standards, and use audit management as a means to encourage suppliers to change their processes so that their products meet these requirements. Thus, in audit management, the manufacturers' management ability must be evaluated through process quality, process techniques, and international environmental standards. Higher quality process derives from consistent management ability, and can reduce supplier material risk.

4.2.3 Occurrence

This study compared the tested values submitted by the laboratory of the case study company with those in the test report produced by the manufacturer. This study examined 272 suppliers according to severity and test difficulty to find the corresponding test values. Not all the laboratory data are disclosed. The laboratory results submitted by the company's suppliers are highly consistent with the results of the test reports. If all the materials can be managed from the source, then—as long as the raw materials and manufacturing processes do not involve hazardous substances—the products will not contain any hazardous substances. No nonconforming product or repeated tests will occur during the product forming or process stage, and no additional testing costs will be incurred.

Due to the space problem, Table 8 only illustrates the highest risk suppliers that RPN = 729. It means that suppliers 14, 93, 116, 220, 23, 66 would be highest risk suppliers. The enterprise should do onsite audition often. The RPN statistics of the 272 supplier data for of different components are shown in Table 9. For those suppliers whose RPN are between 243 and 729 should be monitored regularly. Suppliers that provide plastics must test for chloride (Cl) and bromine (Br) contents, which are mainly contained in the PCB and plastic materials of components. Lead (Pb) content must be tested when the components contain solder or metal alloy. By establishing the study principle, the suppliers must provide SVHCs prior to testing.

5. Conclusions

During evaluation of green suppliers, enterprises currently focus on testing permissible thresholds and hazardous substances specified by the international manufacturers, or any new directives and specifications. Based on the literature review and case analysis, this study suggests that different material categories should have different SVHCs for RoHS and REACH. The material risk is evaluated via XRF data and interval concept, whereas supplier risk is evaluated through FMEA. After the supplier risk RPN is determined using the three risk factors (testing document management, audit sheet management, and laboratory testing management), the green supplier evaluation system can be completed. The UCL and LCL is used to determine the risk suppliers in this method. It can serve as the reference for developing or improving a green supply chain. Furthermore, the method can provide the basis for the substances that different material suppliers must test, enforce supplier compliance, and reduce the time and costs associated with testing. Enterprises can use the method as a reference to introduce and implement their future component testing mechanism. In addition, the selection and discussion of green suppliers are introduced within the ODM sector. The supplier risk and material risk are evaluated. The enterprise can select competitive suppliers within the same material category via scores for RPN of supplier risk, and RoHS and REACH testing items corresponding to the material risk. The enterprise can eliminate noncompliant suppliers, identify new suppliers, and evaluate the potential risk of using individual suppliers.

This study also used three factors—document management, audit management, and testing management, to evaluate supplier risk in individual case analysis. If future data are available and operating conditions permit, it is recommended that other factors may be incorporated into risk evaluation, such as BOM, corporate payment credit, etc., thereby extending the implementation of risk evaluation. Finally, this study only focused on compliance with the RoHS Directive and REACH regulations. However, ODMs will continue to release new products according to the specifications of international manufacturers and EU Directives, and the factors for evaluation of supplier risk and SVHCs corresponding to material risk should therefore be modified accordingly. This is the future goal and direction of the manufacturers. It also needs to be emphasized that the green component may not yield to green final products since the quantity of components in a product is various. The manufactures should further to explore the total solution of green products.

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