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Resources Sustainability through Material Efficiency Strategies: An Insight Study of Electrical and Electronic Companies

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Abstract: The circular economy (CE) is in a growing trend, especially to address the concern of resources sustainability, both from academics as well as industrial practitioners. For manufacturing businesses and services to be sustainable, using materials efficiently is an essential strategy, which is able to enhance the promotion of CE. However, for a developing country like Malaysia, little is known about the ongoing material efficiency strategies among the manufacturers. This paper presents a qualitative investigation of adopting material efficiency strategies in the manufacturing industry. Semi-structured interviews were used to explore the material efficiency strategies at selected Electrical and Electronics (E&E) companies in Malaysia. A list of 11 E&E companies material efficiency strategies were determined and explicated. This paper provides valuable insights to academics and practitioners for a better understanding of the current practices pertaining to the material efficiency strategies in E&E companies in a developing country.

Keywords: circular economy; material efficiency; sustainable manufacturing; waste reduction; waste minimization

1. Introduction

The Circular Economy (CE) concept is in a growing trend in both developed and developing countries, especially to promote the return or recycling of obsolete products through the resource chain [1]. With the growing demand for products and services to satisfy the modern lifestyle, more virgin resources are extracted and harvested in various industries. However, most of the waste generated from industrial activities are not being effectively managed along with their life cycle, inasmuch as the materials and products are not being efficiently reused and recycled or considered unknown [2–4].

In Malaysia, industrialization is the backbone of the country's economic development, especially the manufacturing sectors. However, the expansion of the industry sector contributes significantly to environmental issues, such as e-waste generation [5–8], with a steady growth rate of 3–5% [5,9]. Therefore, the recovery rate of industrial products during their end-of-life is still low, and has now become a critical issue for manufacturers, e.g., electronic devices [7,10,11]. In addition, the issue of material overconsumption presents the most urgent problem faced by most manufacturers. Lovins [4] emphasized that near to a half-trillion tonnes or 99% of raw materials are turned into various forms of

waste across the manufacturing processes annually, and that only 1% of raw materials are built into end products. Therefore, the ways to design and process raw materials need to be urgently reconsidered, especially to counter the inefficient material utilization in the manufacturing sector.

Proficient groundwork and planning during the product design and manufacturing play a significant role in determining the efficiency of the use of materials. Therefore, it is believed that integrating the material efficiency concept in the early stages of product development and the manufacturing process could result in positive changes in the conservation of resources compared to the traditional approach, which focuses on the general product end-of-life recovery activities [12,13]. Several researchers (e.g., [14–16]) have suggested that integrating environmentally related strategies in the early stages of product development could help to minimize the industrial waste flow into the ecosystem.

This paper focuses on the material efficiency strategy, which is one of the important strategies under sustainable manufacturing initiatives [12,13]. Generally, it is found that many environmentally related strategies have the potential to reduce material usage and waste generation. Nevertheless, the material efficiency strategy has received limited attention compared to strategies that manage the product end-of-life [15,17]. A clearer view shows that the classification of material efficiency strategies within the manufacturing industry is still inadequate [13,18], especially the lack of research to present the strategies that are commonly used in each manufacturing industry.

Thus, to fill these gaps, the aim of this study is to identify the current material efficiency strategy of E&E companies in Malaysia. The study could help academics understand the current strategies and the perspectives of E&E practitioners in developing countries, and, together, assist other practitioners of similar companies who wish to commence the journey of achieving material efficiency in their companies.

2. Literature Analysis

Material efficiency can be an effective strategy to enhance sustainable raw material utilization in order to reduce the environmental impacts and fulfilment of the requirements of the circular economy [12,13,15,19–24]. In the manufacturing industry, material efficiency is defined as the practices and strategies to enhance the usability of raw materials without compromising the original functions and purpose of a product [21]. Abdul Rashid et al. [12] suggested that material efficiency could be achieved through collective activities; namely, use less material per product, generate less waste per product, use less energy per product, and generate less toxicity per product. In other recent researches on material efficiency, it was found that material efficiency is tightly linked with three major goals, namely, improve the resource efficiency in an economy or business, reduce the demand on energy for material or product processing, and, finally, reduce the greenhouse gas (GHG) emissions from the involved parties, such as the manufacturer [25–27]. Thus, it can be seen that the study of material efficiency is in a growing trend to project the roadmap of global resource requirements, particularly in the material supply chain with reliance on socio-economic aspects in different manufacturing sectors, country policies, and the needs for sustainable development in preparation for future technological changes [27–29].

On the pathway to practice material efficiency, there are several strategy models and frameworks recorded in the past literature. In the model developed by Lilja [30] and Allwood et al. [13], both authors stressed that material efficiency could be achieved through product design, product consumption, and also during the manufacturing process. Ashby [31] described material efficiency as solutions to drive less material intake into the production through the engineering concept, economic instruments, and also a proper lifestyle. Although there are several frameworks to discuss the material efficiency strategy, it is evident that improvements in product design and manufacturing are the two key areas to achieve material efficiency. In the following sections, the material efficiency strategies conducted in product design and the manufacturing context are discussed. The summary of material efficiency strategies is presented in Table 1.

Table 1. List of material efficiency strategies practiced in the manufacturing industry.

Material Efficiency Area	Strategy	Benefit	Reference
Product design	Less material per unit functions; Design for multiple purposes; Doing with less/doing without; Product light weighting	Reduce material intake; Reduce product size; Reduce product weight; Reduce material intake; Shorten manufacturing and product assembly time	[13,22,30–33]
	Design for longer life	Extend product life cycle; Reduce virgin material extraction	[13,30,31,34]
	Design for remanufacturing	Reduce energy use during manufacturing; Reduce virgin material use	[13,35,36]
	Design for reuse	Extend product life cycle; Reduce energy usage in manufacturing process	[13,22,30,37]
	Design for recycling	Recover material from obsolete product; Reduce virgin material extraction	[13,17,30,31,38,39]
Material sourcing	Material substitution/green material purchase	Ease the manufacturing process; Reduce energy consumption; Ease the material recovery; Reduce manufacturing cost; Reduce solid waste generation	[13,22,30,35,40–44]
	Pre-manufacture part	Reduce machining time; Reduce solid waste generation; Reduce energy consumption;	[30,45]
Manufacturing process	Process efficiency	Reduce solid waste generation; Reduce manufacturing time; Eliminate unnecessary processes; Reduce energy usage	[46–50]
	Yield improvement	Reduce solid waste generation from manufacturing process; Reduce reprocess activities	[13,28,30,51]
	By-product recycling	Recover the solid waste into resource	[30,52,53]
Product Distribution	Green packaging	Recovery material from packaging	[22,54–56]
	Bulk packaging	Reduce packaging material use	[57]
	Lightweight packaging	Reduce packaging material use	[57]
	Returnable packaging	Extend product life cycle; Reduce packaging waste	[22,58]

2.1. Material Efficiency Considerations in Product Design

Product design plays an important role in promoting material efficiency. Allwood et al. [13] suggested four major strategies that could be used to enhance material efficiency in product design: (1) Designing products with less material; (2) Design longer-lasting products; (3) Component re-use; and (4) Design for material recovery.

In the design context, one of the common strategies to be used is “designing a product with less material”, which can be achieved through reducing the overall size, the number of parts, or the weight of the parts of the product [22,31]. This strategy is among the simplest yet most challenging ways of reducing the overall environmental impact. However, the light weight of products, such as electronic equipment, does not guarantee minimization of the impact on the environment if the materials used are highly hazardous [59]. This practice is becoming more popular and widely used to perform multi-tasking or multi-functions, which could decrease material utilization and then contribute to material efficiency [20,30,32]. The use of standard parts in production is also a must have strategy to reduce material waste, as it shortens the assembly time, and eliminates unnecessary parts that consume more material [60,61]. Furthermore, with the advancement of technology, ultra-light materials are increasing in popularity to replace heavier materials for achieving material efficiency purposes [33]. However, ultra-light materials entail higher costs.

In designing for long-lasting products, the consistent use of high quality or environmentally friendly materials is needed to avoid failure and waste due to poor material properties [31,62]. Improving the mechanical properties of materials is the key factor towards achieving material efficiency because it extends the product life [30,34]. Many products are now being embedded with the feature of the design for a longer life; for example, improving the mechanical design of the product, especially at critical points, and the use of durable materials to extend the product life. Therefore, the user could enjoy the longer product warranty given, which, in turn, reflects the better quality and durability of the product. Making products that can last longer definitely helps to reduce waste and helps to reduce the usage of virgin materials. However, this strategy must be coupled with other strategies, such as an imbedded service system to ensure profit for manufacturers and provide after-sales support for the customer [63].

To improve product usability, designing products for part recovery with the intention of part reuse, remanufacturing and recycling is gaining popularity, as it enables producers to recover and minimize the waste before the product is sent to landfill [13,35]. With these considerations, more industries are encouraged to design their product in modular form to ease product reuse, repair, and extend the product life cycle [13,22,30,37]. Practicing product reuse could prevent energy waste for producing a new part, and extend the product life cycle. For product remanufacturing, the automotive industry is one of the fast-growing industries that practices this strategy to reduce the material wastage by recovering and returning the malfunctioning products to nearly new condition [13,36]. As for design for recycling, the easiest way is to use recyclable raw materials [13,17,30,31,38,39]. In relation to the rapid technological change, designing electronic products that could be dismantled for recycling would contribute significantly to the material recovery rate [59]. For example, the recycling of electronic devices enables the recovery of precious materials, such as gold and copper. However, although e-waste still continues to rise due to limited recycling, it is embedded in the product design in E&E products [35].

2.2. Material Efficiency during Material Sourcing

Materials should be consumed more effectively, especially precious and non-renewable materials. Material substitution can be done by selecting non-rare materials with similar characteristics that are in plentiful supply [35]. Thus, material substitution, which is used to enhance product performance and to ease the manufacturing process, is a frequently found strategy that appears in many industries, such as the manufacturing industry [13,22,30], food packaging [40], and chemical processing industry [41]. Most of the applications relating to material substitution are also due to the need to comply with

environmental policies in order to minimize the environmental impact, such as reducing CO₂ emissions [40]. In addition, complying with the Restriction of Hazardous Substances (RoHS) directives can limit the E&E industry's use of hazardous materials that are very dangerous to recycle [43], as well as to improve the performance and reduce the manufacturing costs [13].

In the context of the material supply chain, the purchase of pre-manufactured or prefabricated parts contributes to reducing unnecessary industrial wastage through the elimination of the primary trimming process, such as by-product materials, energy consumption in the machine, and other resources [30,45]. Therefore, in dealing with the supplier, it is important to select a supplier with the necessary knowledge and green capabilities, such as ISO14001 compliance. Manufacturers need to share the information about the product specifications and requirements with the supplier in order to fulfil green performance [42].

2.3. Material Efficiency Considerations during the Manufacturing Process

Material efficiency could be achieved through increasing the efficiency of the production operations, which could be done by simplifying the involved manufacturing processes or increasing the process efficiency. By reducing the processing steps, potential solid waste generation could be reduced through eliminating unnecessary secondary processes [46]. Furthermore, batch processing is one of the widely used practices to reduce the process steps and shorten the total production lines [47]. In addition, by simplifying the operations in the production lines through appropriate improvements, less energy consumption could be achieved [48,49]. Besides, selecting an appropriate manufacturing strategy not only helps to shorten the overall production time, but also minimizes waste [30,50], which could be done through, for example, reducing the processing steps, or improvement in material handling, such as the use of a robotic arm to reduce the chance of mishandling if manually conducted by humans.

To achieve high material yield improvement, efficient production and the process setup play a significant role. Some of the common activities to improve the product yield during manufacturing operations are to minimize the product testing, reduce the trimmed material to be scrapped, and reduce materials to be reprocessed [13,28,30,51]. In addition, for recovering the generated solid waste along the production, a by-product recycling strategy should be introduced, especially for recyclable materials, such as metals and powder scraps [30,52,53]. By-product recycling must be supported by the available recycling facilities in addition to the infrastructure of the company [53]. However, most of the time, manufacturers still prefer to sell their product scraps to third parties, such as recyclers because this is considered preferable to investing in an internal recycling system.

2.4. Material Efficiency during Product Distribution

The basic purpose of packaging is to provide protection to the products. Every product needs to be packed before shipment to a destination or customer. However, each year the materials consumed for packaging are increasing, especially from the industrialized countries [64]. Thus, this makes the sustainable use of raw materials in the product packaging very important. In respect of material efficiency, the use of recyclable packaging materials is one of the effective strategies to reduce waste generation [22,54]. As a result, the use of recyclable materials for packaging becomes an obvious strategy to extend the life cycle of raw materials, e.g., paper, cardboard, and wood [55,56].

Material efficiency can also be achieved through packaging initiatives; for example, products could be packed in bulk rather than as single units to save space and the cost of transportation [57]. In addition, manufacturers should use a lightweight packaging design to reduce the weight of heavier packaging, and minimize the amount of material to pack the products. [57]. Another option is to use returnable packaging to the manufacturer for reuse, for example, substitute cardboard boxes with returnable wooden crates [22,58].

3. Research Design

Given the limited evidence of material efficiency solutions in the E&E sector, a qualitative method—semi-structured interviews—was used to explore unknown phenomena in this industry [65, 66]. Face-to-face interview sessions were conducted with an average of 60 min each at the industry location. In this study, the interview questions were conceptualized based on the “what” and “how” aspect, for example: “What are the strategies available to reduce material consumption?” “How can solid waste generation be reduced?” In addition, reflexivity questions were raised with the interviewee to verify the claimed strategies during the interview session. Examples of interview questions and reflexivity questions are shown in Appendix A.

By referring to the Federation of Malaysia Manufacturing Directory 2016, the recruitment of the E&E Companies for the interviews was carefully designed to ensure that the company and personnel selected were relevant to the study. Examples of the selection criteria are focusing on ISO 14001 certified E&E companies to ensure the companies interviewed are well aware of environmentally benign strategies in their operation. This was followed by selecting E&E companies that were involved in product design and manufacturing. As for the selection of interviewees, personnel with at least five years working experience and familiar with material purchase, product design or material processing were selected. These practitioners had to be decision-makers in establishing company policy, or involved in improving the company’s productivity. The recruitment process was conducted using email and phone calls. The interview questions were emailed to the interested company before commencement of the interview session.

A total of 85 E&E companies, particularly medium to large sized companies, were contacted. However, only seven companies agreed to participate in the interview sessions, as listed in Table 2. These companies are large with more than 250 employees. The key-informants or interviewees from these companies were the production manager, packaging manager, packaging director, principal designer, material specialist, senior engineer, and Environmental-Health-Safety (EHS) manager. The participating companies were labelled C1 to C7 to ensure data confidentiality. Although only seven companies took part in the qualitative study, the richness and rigorous analysis of the data are the key elements to represent the consent of the E&E companies towards the investigated subject (e.g., material efficiency strategy) [67].

Table 2. List of case study companies.

Case Study Company	ISO14001 Compliance	Product/ Service	Key-Informant (Experiences)	Origin Country, Size	Department/Unit
C1	Yes	Integrated Circuit	Senior Engineer (Quality control) (8 years)	Germany, Large (>4000 employees)	Production; Quality control unit
C2	Yes	Circuit design, mechanical design and assembly	Material Specialist (9 years)	USA, Large (>2000 employees)	Research and Development unit; Design
C3	Yes	Integrated circuit	Packaging Department Director (10 years), Senior engineer (8 years)	USA, Large (>1000 employees)	Management; Design unit; packaging unit
C4	Yes	Integrated circuit, circuit design and assembly	EHS Manager (12 years)	Malaysia, Large (>1000 employees)	Environmental and safety unit
C5	Yes	Solar cell, solar panel	Packaging manager (10 years)	USA, Large (>1500 employees)	Production unit; Packaging unit
C6	Yes	TV (video and audio system), LED display unit	Senior engineer (7 years)	Japan, Large (>1500 employees)	Design unit;
C7	Yes	TV (video and audio system), LED display unit	Principal designer (10 years)	Netherlands, Large (>500 employees)	Research and Development unit; Design unit

In this study, one project leader together with three research assistants interviewed the industry practitioners. For the purpose of data analysis, the interviews were recorded and then transcribed verbatim, which amounted to 120 pages for seven interviews. The transcripts were then analysed using the thematic analysis approach by all the participating researchers. Five important steps are involved in performing thematic analysis [68,69], which are shown in detail in Table 3. Examples of the research themes extraction from the verbatim transcripts are shown in Figure 1. In order to ensure the research quality, as well as the reliability and credibility of the findings, several techniques, such as audit trail and member checking, were employed [70]. An audit trail was used to enhance the trustworthiness of the interpreted themes [71], and member checking was performed with other research members to check the synthesized themes. The consensus concerning the themes of the data were measured using the Kappa index or a similarity index (>0.6) [72]. The interview themes with significant differences were further discussed and rephrased. Verification of the developed themes were sent to the participating practitioners to ensure the validity of the extracted interview theme.

Table 3. Qualitative data analysis process (source: [69]).

Step	Data Analysis Process	Activity
1	Transcribe Data	Researcher transcribes verbatim the recorded interview data. Repeated reading of the transcripts in order to become familiar with the transcripts.
2	Generate code	Researcher codes the interesting and relevant data (short phrases, sentences, or the entire dataset).
3	Build Theme	Researcher searches for and reviews the available themes to be used to describe the identified codes.
4	Define Theme	Researcher clarifies the themes to be used by presenting the clear relationship to the data codes.
5	Produce Findings	Researcher analyses the results from the themes and codes, and relates these discoveries to scholarly findings.

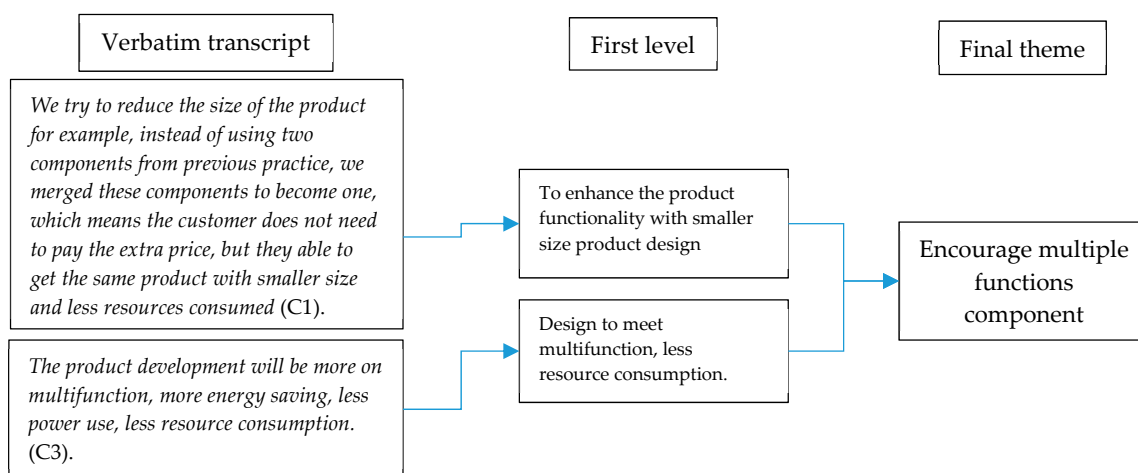


Figure 1. Example of extraction of material efficiency theme based on information obtained with case studies C1 and C3.

4. E&E's Material Efficiency Strategies

This study identifies the material efficiency strategies in the E&E sector in the Malaysian context. In general, most of the E&E companies understood the material efficiency concept in terms of the reduction of material usage in order to reduce cost. It can be seen from this study that practicing the material efficiency strategy as a way of reducing the environmental impact is not a new concept for Malaysian E&E manufacturers. Across the interviews, all the companies reacted positively

to the initiative to reduce the environmental impacts and concerns about less material utilization. Furthermore, as there are no specific governmental regulations concerning material efficiency, it is very dependent on an industry's own initiatives.

The strategy to achieve material efficiency in E&E companies is covered in four main phases, namely, product design, material sourcing, manufacturing process, and product packaging and distribution. The examples of the material efficiency strategies with selected interview quotations are presented in Appendix B. Referring to Table 4 below, it presents the complete list of material efficiency strategies gathered from Malaysia's E&E companies. From Table 4, it can be seen that E&E companies are concentrating on product design, material sourcing, and manufacturing phases, but there is little improvement in terms of the packaging process in respect of material efficiency efforts. Examples of the strategy activities are also presented in this table.

Table 4. List of material efficiency strategies from E&E companies.

Area	Criteria	Example of Activities	Semi-Structured Interview						
			C1	C2	C3	C4	C5	C6	C7
Product design	Fabricate with less components	<ul style="list-style-type: none"> • Thinner PCB board design • Practice screwless design in enclosure • Eliminate unnecessary design features 	x		x	x	x	x	
	Design for ease recovery	<ul style="list-style-type: none"> • Incorporate recyclable materials (Pre-set the incoming part with certain recycled materials; Easy to dismantle components) 				x			
	Design with longer life components	<ul style="list-style-type: none"> • Enhance mechanical properties of material. (Ease of maintenance/upgrade of component) 			x				
	Encourage multiple functions component	<ul style="list-style-type: none"> • Improve the chipset capacity to reduce the product size (multi-function chipset) (Offer integrated part to replace multiple modules) 	x		x		x	x	
Material sourcing	Low environmental impacts material substitution	<ul style="list-style-type: none"> • Change to easy to recycle substances (lead-free and halogen free substances) 	x	x	x	x	x	x	x
	Pre-manufactured part purchase	<ul style="list-style-type: none"> • Purchase materials that require less or no secondary process (Acquire exact dimensions and specification part) 	x	x					x
Manufacturing process	Close to tolerance machining	<ul style="list-style-type: none"> • Apply precision jig and fixture (Minimum material contact points requirement) 	x		x	x	x	x	x
	Reduce production changeover	<ul style="list-style-type: none"> • Reduce the changeover frequency to reduce material wastage (Standardization in changeover, eliminate unnecessary steps which involve material wastage) 	x	x		x	x		x

Table 4. Cont.

Area	Criteria	Example of Activities	Semi-Structured Interview						
			C1	C2	C3	C4	C5	C6	C7
Product Distribution	Green packaging	<ul style="list-style-type: none"> Use of recyclable material such as cardboard for packing 		x		x		x	x
	Returnable packaging	<ul style="list-style-type: none"> Introduce plastic pallet which could be reused and last longer 							x
	Bulk packaging for non-critical components	<ul style="list-style-type: none"> Avoid single part packaging to reduce the material (Optimum space use in packaging design) 				x			

5. Discussion and Research Implications

5.1. E&E Material Efficiency Strategy in Product Design and Material Sourcing

It has been proven that product development is one of the core aspects in deciding the success of a product from the aspect of manufacturability, improving the product life cycle performance, as well as reducing the environmental impacts [18,73].

In reducing the material for E&E products, fabricating with less material is the most direct and collectively found practice to achieve material efficiency. For example, three claimed activities that are commonly being done by the E&E companies are thinner PCB board design, practice screwless product design, such as apply snap fit feature, and eliminate unnecessary features or outdated features (e.g., remove infra-red feature in mobile phone).

To recover the used raw material or part from the product during its end-of-life, some E&E companies suggested design for easy recovery and design with longer life components. The first strategy can be achieved through easily dismantled components for recycling (e.g., larger components with higher precious material contents, such as gold and copper). The design with longer life practice can be done using high durability components (e.g., components able to resist high heat, water resistant, and ease of service or upgrade). However, both strategies gained limited response from the E&E sector due to the difficulty in recycling complex e-waste [74–76], and due to the poor recycling technologies that are available [35,74]. As a result, the rapid change in the E&E industry has discouraged designing products with longer life because of the technology advancements, which are growing very fast in this sector. Therefore, changes in terms of prolonging the product life are less practical due to the fast rate of products becoming obsolete [74,76], and less economic advantages to the manufacturer.

In this study, the encouragement of a multiple function component is another strategy employed by four E&E companies (e.g., C1, C3, C5, and C6). For example, different product features are merged to enable more inputs-outputs (I/O) capability (e.g., multifunctional chipset); this strategy is in-line with the existing strategies posted by the researchers [13,31]. Across the interview sessions, we understood that Company C1 was requested by their supplier to merge the product feature into one chipset to replace the old module, which was bulky and expensive. The new chipset design integrates more functions into a single chipset to reduce its size and total material used. In addition, it could help reduce the total material used and the weight of a product by delivering the same or better performance. However, this strategy needs to complement better material quality due to many functionalities [77], and it is reliant on the collaboration between many suppliers [13,20,22,31].

In terms of the material sourcing aspect, low environmental impact material substitution was found to be a popular practice in the E&E sector to achieve material efficiency. Seven companies (C1-C7) preferred to substitute their existing material with recyclable materials as an effective way to achieve material efficiency (e.g., lead-free and halogen-free substances). These companies claimed that the use of the environmentally friendly material is compulsory, especially for electronic devices, to reduce the potential e-waste issue, and ease the product recycling process [44]. Similar to the past research,

the use of non-renewable materials, such as highly toxic lead substances, will discourage material recovery activities, such as recycling activity [35,43,53]. This is because the current technologies are still inadequate, especially for managing and processing these high toxicity materials in which the recycling tasks are dangerous to the recyclers health, the recycling process consumes high energy compared to virgin material extraction, and also because low profit is gained from the recycling activities [75,78].

In order to use the material efficiently, three companies (C1, C2, and C7) agreed that the efficient intake of raw materials to reduce solid waste generation is essential. For example, the purchase of pre-manufactured parts could avoid the secondary manufacturing process. This finding is in-line with the literature, such as pre-manufactured parts are commonly used in many industries to reduce the material required and time wastage from machining [30]. One example of pre-manufactured part purchase by a company is the wafer for the purpose of solar cell fabrication (e.g., C7). Another important element in the pre-manufactured part purchase is information sharing with the suppliers. The information sharing can be done by specifying the material requirements to their supplier, especially the shape, size, and mechanical properties, and percentage of recycled materials [42].

5.2. E&E Material Efficiency in Manufacturing Processes

Achieving material efficiency in the manufacturing phase is challenging due to the complexity of the manufacturing process and complications in product design. In the E&E sector, material yield improvement has gained comparatively high attention due to the nature of the working environment in the E&E sector; the yield should be higher because of the utilization of high precision and advanced technologies. One of the companies (C1) claimed to minimize the material wastage by improving the jig clamping contact or performing close to tolerance machining. In previous research, this practice has been introduced in various sectors, such as the wafer industry [51]. Two companies (C1, C5) carried out a strategy to optimize the usage of lead frame machining during the integrated chip bonding process. Also, close to tolerance cutting is being applied to reduce the cut edge of the wafer for the integrated circuit to minimize the scrap generation. This is similar to the fundamental concept of the process yield of raw materials, which has been discussed by Allwood et al. [13].

In the process efficiency strategy, reducing changeover frequency is another practice that is suggested as being able to save more materials, particularly materials for production setup, testing purposes, and pre-run before the first article is confirmed. This finding confirms the study by Lilja [30] who stated that process efficiency largely depends on good production planning. For example, optimising the batch processing and performing standardization in the setup of various products (consolidate closest product types) is one of the strategies used in company C1 to reduce unnecessary solid waste generation and reduce the frequency of changeovers.

5.3. E&E Material Efficiency Strategy in Product Distribution

In respect of product distribution; the participating companies imposed a green packaging strategy to prolong the lifetime of the material. This initiative was done by utilizing packaging materials that are made from recyclable sources, e.g., cardboard packaging. This practice is becoming a trend among manufacturers due to the increment of responsibility towards environmental protection [56]. The efficient use of materials in the packaging design could be employed to ensure that the products are packed within a limited space by optimizing the space, such as bulk packaging, which was mentioned in a previous study [57]. By implementing bulk packaging for a non-critical component, the participating companies have found that it can reduce inventory space and the related cost of logistics. Although packaging strategies were the issue least discussed across the interviews, this does not mean that the case study companies are not well aware of the importance of using materials efficiently. The reasons are because the materials used for the packaging are not critical and the use of recyclable materials, such as cardboard, is obvious. Therefore, the potential changes in packaging are presumed to be limited to the E&E sector. In short, companies from the E&E sector are of the opinion that it is not necessary to improve material efficiency in their packaging process.

5.4. Research Limitations

Exploring data from the industry context using the qualitative approach is a challenging task, especially in developing countries such as Malaysia. In this study, the limited participation of the industry could possibly influence the insightful theory development of material efficiency implementation. The reasons could be due to the issue of company policy restrictions and the lack of interest among the practitioners. However, these shortcomings could be improved by offering a variety of interview methods, such as teleconference interviews, email interviews, phone interviews, and organizing workshops.

6. Conclusions

Material efficiency plays a vital role in promoting the Circular Economy through minimizing the resource utilization, and returning obsolete products to the material chain. Different types of manufacturing companies perceive the material efficiency strategy differently. Therefore, understanding the material efficiency strategies in a specific industry is essential to discover an effective solution for sustainable material utilization. This research applied qualitative study methodology to investigate and determine the initiatives of E&E companies in achieving material efficiency.

This study has confirmed the current practices of the E&E sector in material efficiency efforts. A list of 11 material efficiency strategies were determined across the E&E Companies: fabricate with less components, design for ease of recovery, design with a longer life component, encourage multiple functions component, lower environmental impact material substitution, pre-manufacture part purchase, close to tolerance machining, reduce production changeover, include green packaging, create returnable packaging, and bulk packaging for non-critical components. As indicated in this study, much effort has been made to ameliorate the materials and product design in terms of material efficiency for the fulfilment of environmental compliance. Whereas, limited manufacturing strategies are shown because they closely depend on the proposed changes in product design and available machinery limitations. Lastly, the packaging and distribution strategies shown are the conspicuous strategies that are commonly practiced in the manufacturing sector.

This study consists of raw data from E&E industry experts, which were collected and carefully analysed using qualitative methodology. The findings are insightful and unique whereby the extracted verbatim data distinctively represent the current thoughts of the E&E industry in a developing country in perceiving material efficiency. In addition, the synthesized material efficiency activities are unique to indicate how the high-end industry applies knowledge in product design, material sourcing, manufacturing, and packaging to achieve material efficiency (refer to the example activities in Table 4). These findings provide important information to support the area of material efficiency, whereby the findings consist of developing country data (Malaysia), which could be used as guidelines for similar types of study with a different demographic configuration.

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Appendix A

Interview Questions

1. Is your company aware of the importance of integrating a green or environmental strategy into the product design and manufacturing process?
2. Does your company use any tactics or strategies to reduce material usage and waste in any way (material purchasing, design, manufacturing, and packaging and distribution)? If yes, please explain how?
3. What is the common solid waste in your company? Are any strategies employed to reduce this waste?
4. Does your company production line generate any toxic waste? What are the strategies being practiced by your company to reduce the toxic waste?

Examples of Follow-Up Reflexivity Questions:

1. How to make your product lighter?
2. How to make your production line greener and sustainable?
3. How to manage the generated waste along the production lines?
4. How to control the scrap generation along the production lines?

Appendix B

Table A1. Examples of quotation and theme generation.

Area	Quotations	Final Theme
Product design	"... what customer tries to do is to request a one off part to be integrated with other parts to make it more efficient and smaller, but the component generally can do two functions, compared to what we see previously they need two components to do it."	Design for multiple purposes
	"... the green compound used currently has to last at least 8 years. That's why the material supplier has to come out with the component, parts, and the technology to make it longer life."	Design for longer life
	"we already design to try to make it smaller, compared to last time, one wafer was possible to produce about 500 chips; however, now, because of better design, with the latest advanced technology, one wafer with same size they can produce 1000 chips."	Less material per unit of function
	"if it is a recyclable part, we will put a recycle mark there, that is why we have a recycle mark on each of our parts,"	Design for material recovery
Material sourcing	"We have to make all the part's using green materials throughout. So far, we don't have any issues to substitute green materials"	Material substitution
	"We are buying wafers that are already in a sliced shape, which is a good wafer shape, Eventually, our waste would be the damaged wafer."	Pre-fabricated part purchase
Manufacturing process	"We try to reduce the copper usage, meaning that we have the print and same frame size, but want to produce more parts."	Yield improvement
	"...we try to simplify the design with less processes into our design, or in other words we try not to complicate the process in the manufacturing of our design."	Process efficiency

Table A1. Cont.

Area	Quotations	Final Theme
Product Distribution	“We have packaging specs such as the materials and the shape of packaging. So, the supplier of the packaging needs to comply with it”	Recyclable packaging
	“In our packaging, we increased the quantity in our inner boxes. From 14,000 in a master box, we increase to 36,000. Eventually, it is material efficiency; we have increased the packaging in the inner boxes into a master box 2.5 times more. We save on our packaging and we also save on our transportation cost.”	Bulk packaging
	“We also try to reuse the plastic pallet packaging, because plastic pallets are tougher, but the cost is very high, you need to ensure they are returnable from your partners”	Returnable packaging

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