Development of the Material Security Database for Malaysia Assisting the Product Recycling Desirability Model

This report is submitted in accordance with requirement of the University Teknikal Malaysia Melaka (UTeM) for Bachelor Degree of Manufacturing Engineering (Hons.)

by

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DECLARATION

I hereby, declared this report entitled “Development of Material Security Database for Malaysia Assisting the Product Recycling Desirability Model” is the result of my own research except as cited in references.

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APPROVAL

This report is submitted to the Faculty of Manufacturing Engineering of Universiti Teknikal Malaysia Melaka as a partial fulfilment of the requirement for Degree of Manufacturing Engineering (Hons). The member of the supervisory committee is as follow:

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(Ts. Dr. Al Amin Bin Mohamed Sultan)

ABSTRAK

Pada hari ini, masalah pembaziran bahan adalah isu yang serius di negara yang membangun seperti di Malaysia. Terdapat satu model yang bernama Model Kehendak Kitar Semula Produk dapat meningkatkan kadar kitar semula. Namun begitu, model ini todak dapat digunapakai di Malaysia sebab kekurangan satu unsur, iaitu Index Keselamatan bahan. Satu pangkalan data diperlukan untuk menentukan Index Keselamatan Bahan. Terdapat dua dimensi yang diperlukan untuk membina pangkalan data keselamatan bahan, iaitu risiko bekalan dan risiko bahan. Bagi risiko bekalan, terdapat empat penunjuk, antaranya ialah ketidakcukupan bahan, penawaran monopoli, kestabilan politik, dan kerentanan perubahan iklim. Bagi risiko bahan, antara empat penunjuknya ialah tahap penggunaan di Malaysia, kebolehtukaran, potensi pemanasan global, dan jumlah keperluan bahan. Setiap penunjuk ada cara permakahan tersendiri untuk menilai keselamatan and kritikan bahan. Selepas itu, bahan-bahan yang telah dimarkah plot dalam matrik bahan keselamatan untuk mendapat bahan yang paling kritikal. Dalam projek ini, terdapat 89 bahan telah dikenalpasti sebagai bahan yang kritikal, antara lima bahan yang paling kritikal ialah Paladium, Rodium, Emas, Platinum dan Telurium. Dasar dan inisiatif kitar semula dapat diaplikasikan secara strategis oleh kerajaan, inisiatif ini termasuk implementasi Model Kehendak Kitar Semula Produk dengan mengembangkan pangkalan data keselamatan bahan untuk ekonomi Malaysia.

ABSTRACT

Today, in developing countries like Malaysia, the problem of material waste is a critical concern. There is a recycling model named the Product Recycling Desirability Model was able to boost the recycling rate. However, the model is not applicable to Malaysia because of missing element of material security index. To determine the material security index, a database is needed. There are two dimensions used to develop material security database, which were supply risk and material risk. There are four measures of supply risk, which are scarcity, monopoly supply, political stability and climate change vulnerability. While the four indicators for material risk are Malaysia's consumption levels, substitutability, global warming potential and total material requirements. Each indicator had its own scoring method for evaluating the security and criticality of the material. Then the materials plotted on material security matrix to determine the most critical material. In this project, critical materials had been identified and assessed where 89 materials were classified as a critical for Malaysia with the five top ranked material are Palladium, Rhodium, Gold, Platinum and Tellurium. The outcome of this project was used in the Product Recycling Desirability Model to assess the desirability index for recycling products. By having the material list, the recycling policies and initiatives can be strategically enforced by the government, including the implementation of Product Recycling Desirability Model, by developing the material security database for the Malaysia's economy.

DEDICATION

Only

My beloved father, Yoong Chee Seng

My appreciated mother, Lim Sau Heong

My adored sister and brother, Yoong Li Suen and Yoong Li Yang

For giving me moral support, money, cooperation, encouragement and also understandings

Thank You So much & Love You All Forever

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TABLE OF CONTENT

CHAPTER 1: INTRODUCTION

CHAPTER 2: LITERATURE REVIEW

CHAPTER 3: METHODOLOGY

CHAPTER 4: RESULTS AND DISCUSSIONS

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

2-D - 2 Dimension

3-D - 3 Dimension

3R - Reduce, Reuse, Recycle

AHP - Assess Analytic Hierarchy Process

CE - Circular Economy

CEEW - Council on Energy, Environment and Water

DOE - Department of Energy Malaysia

Dy - Dysprosium

E&E - Electric and Electronics

ELVs - End of Life Vehicles

EU - European Union

E-waste - Electronic Waste

GDP - Gross Domestic Product

HDD - Hard Disk Drive

IPI - Industrial Production Index

JMG - Jabatan Mineral dan Geosains Malaysia

LCA - Life Cycle Assessment

LCD - Liquid Crystal Display

LIBs - Lithium-Ion Batteries

MSI - Material Security Index

NASA - National Aeronautics and Space Administration

Nd - Neodymium

PCB - Printed Circuit Board

PGM - Platinum-Group Metals

Pr - Praseodymium

R&D - Research and Development

RDI - Recycling Desirability Index

REE - Rare Earth Element

RPA - Recycling Potential Assessment

TMR - Total Material Requirements

TRL - Technology Readiness Level

UK - United Kingdom

US - United States

USA - United States of America

WEE - Waste Electric and Electronic Equipment

LIST OF SYMBOLS

% - Percentage

Kg - Kilogram

pH - potential of Hydrogen

RM - Ringgit Malaysia

USD - United States Dollar

Tons - Unit of measure weight, tonne

CHAPTER 1

INTRODUCTION

1.1 Background

Nowadays, the material wastes problem is a serious issue in developing countries such as Malaysia. The reason for this issue is the value of end-of-life products are not given more attention. Most of the products were send to landfill in its end-of-life. So, recycling is very important step to overcome this wastes problem. Recycling can reduce the need for extracting and refining virgin raw materials by recycled the useable materials from end-of-life products, at the same time can reduce the amounts of end-of-life products dumped into landfill. Therefore, it is necessary for Malaysia to have a measure or method to assess the importance of the products for recycling based on the country's economy.

Material security, also known as material criticality is the concept of evaluation on certain material based on different factors. The factors can be geological deposit, social issues, recycling potential, regulatory structure, environmental issues and sustainability (Graedel & Nuss, 2014). So, the material security can be defined as a strategy to determine a material criticality and evaluate the material from varies parameters and indicators. The material security also expressed as material scarcity or resource efficiency (Hollins, 2008). The factors and indicators of assessment of material security is determined by the scope of research. However, there is no perfect or constant factors or indicators for the assessment of material security. The material security plays a key role in material selection, product design, material recycling decision, as well as in investment decision. The result of the criticality assessment is to obtain the list of critical material and the list of critical material is useful to identify and prioritize materials concern (Fortier et al., 2018).

Recently the worldwide market for semiconductor industries is growing at 15% per year. This phenomenon causes the semiconductor industry has been one of the most important sectors for economy growth (Izumi, 2004). Most of the raw material that used in semiconductor manufacturing is included in the list of material security. However, the production of these raw material include REE’s is concentrated and monopolised by small number of countries only. This situation has triggered the manufacturer to find a solution to sustain the supply of these raw material (European Commission, 2014). One of the solutions is recycled the old electronic product and extracted the useable material, such as gold, copper, nickel, indium etc. There are studies that introduced some recycling model, while in this research the model referenced is Product Recycling Desirability Model.

The concept of material security can be used to develop the Product Recycling Desirability Model (PRDM) (Sultan et al., 2017) . This model can identify the highly desirable product for recycling and strategically prioritise them based on three critical factors that had been assessed by the study in the UK and was successfully applied to several cases in US, EU, India and China. Moreover, the material security plays a key role in material selection, product design, material recycling decision, as well as in investment decision. The concept of material security also able to sustain the economy, reduce the environmental issues, reduce the manufacturing cost, and prevent shortage of material in future demand (Speirs & Gross, 2013). This is because thee assessment of material security is useful to monitor the consumption pattern of a mineral across the industrial sectors and contribution of the material to overall economy (Gupta et al., 2016).

In the 21st century, the global raw material demand patterns were remodelled due to the developing lifestyles, development of new technologies, market dynamics and government policies (Erdmann & Graedel, 2011). The assessment of material security could be conducted by different methodologies. A variety of dimension and factors can be chosen to conduct the assessment of material security. The assessment’s dimensions can be supply risk, impact of supply restriction, economic importance, recycling, political factors, environmental implications etc.

The concept of material security is a matter of concern for the global economy. In order to determine the critical material, also known as insecure material, a framework was developed by Erdmann and Graedel (2011). There are two main dimension that used to determine the critical material, which are material risk and supply risk. For the material risk criteria contain global consumption level, lack of substitutability, global warming potential and total material requirement. While for supply criteria contains scarcity, monopoly supply, political instability, and vulnerability to the effects of climate change (Hollins, 2008). The list of critical material can be used as guideline for recycling process. The supply risk dimension goes beyond output concentration and takes into account other considerations, such as substitutability and recyclability. If a material has high functional substitutability, then it can lower its risks (Gupta et al., 2016).

There are several countries have start to conduct the studies on assessment of material security such as EU UK, U.S, India and Japan (Devauze, 2017; Hollins, 2008; Fortier et al., 2018; Gupta et al., 2016; Hatayama & Tahara, 2015). In EU, the criticality of material is used to strengthen the industrial competitiveness by implement the EU industrial policy. This can increase the overall competitiveness of the EU economy. With the list of critical of material, it can use to help prioritise needs and actions. Furthermore, it can help to promote the European production of critical raw materials and encourage the launching of new mining and recycling activities (Devauze, 2017). In UK, the material security is conducted to develop the recycle desirability model. This model can identify the highly desirable product for recycling. In other words, it can develop a model that can prioritising recycling of end-of-life products in a circular economy(Mohamed Sultan et al., 2017) .

In India, material security is conducted to solve the two main problems, which is lack of suitable technology adoption and inefficiency policy mechanism to drive mining and exploration. A mineral or material will restrict when there are sudden supply shocks in the supply chain, it can be more serious when there are no substitutes available in specific applications. The benefit for the study about the criticality of material is offered policy makers a detailed analysis on the determinants of criticality associated with minerals and the economic importance of minerals (Gupta et al., 2016).

In Malaysia, the main contributor for Malaysia economy is manufacturing industry. However, the growth of manufacturing industry especially E&E industry has created varies challenges to manufacturer, such as increase the consumption level of raw material and cause some rare materials became scare and the end-of-life product is not utilized properly. This situation can influence the recycling rate in Malaysia. In Malaysia, the recycling rate of electric and electronic products and automotive products are relatively low, the overall recycling rate in 2015 is only 10.5% and estimate in 2020 the recycling rate can increase to 22% (PEMANDU, 2015). While recycling rate in Singapore has 60.6% in 2015 (European Environmental Bureau & Eunomia, 2017). So, it is important for Malaysia to develop a strategy that can help manufacturing companies especially E&E and automotive sectors to achieve sustainability in their production and increase material efficiency.

There are a few reasons that trigger the conducting of material criticality assessments. It includes the increasing and new demand for materials from developing economies, demand for wider range of materials inputs from new technologies, concentrations of production, creating supply monopoly and recognition of the social and environmental consequences of mining. The list of critical material can use to make recommendations and suggestion for mitigating actions, including the need for investigation and policies to reduce future supply restrictions (Lloyd et al., 2012).

There are several determinants that needed in assessing supply risk. There are five main determinants that listed in many reports, which is geological, technical, political, environmental and social, and economic (Lloyd et al., 2012). The geological, technological and economic element is comprised of two equally weighted indicator, one is examines the relative abundance of the metal and the other is percentage of the metal mined as a companion (Graedel et al., 2012). For the environmental and social indicators, the two indicators can influence and inhibit the primary production. Environmental factor is more likely to restrict material supply than physical scarcity. For example, international and national laws curbing greenhouse gas emissions may come to restrict the more carbon-intensive extraction processes required for a range of minerals. In the Hollins (2008), it was used two proxies for environmental impacts, which are global warming potential and total material requirement. The assessment in determine critical material can affect by the future demand as well. Future demand is the key determinant of its future availability. There are two factors that used in criticality assessment, which are future demand projections and substitutability (Speirs & Gross, 2013). Normally a material that listed in critical material list has low mining rate and recycling rate, so it should improve its resource efficiency to prevent restriction of the material.

1.2 Problem Statement

In year 2020, Malaysia's industrial production index (IPI) had grown up by 0.6 percent. The growth of the IPI was driven by the increase in the index of manufacturing. The major sectors that contribute the rise of index of manufacturing was non-metallic mineral, basic metal and fabricated metal products. The information shows that the capacity of used of raw material is increasing and this may cause the restriction of material.

A strategic decision-making tool is a necessity to identify the important materials and products towards prioritising end-of-life waste for recycling. Product Recycling Desirability Model is one of the tools that successfully developed and applied to the UK, US, China, and India. However, the model is not applicable to Malaysia yet because the missing parameter and dimension that also known as material security index for Malaysia. This also led to the missing opportunity for the government to strategically plan the recycling initiatives by considering the importance materials based on Malaysian economy. Hence, the development of material security can be one of the parameters of the model and it may help to assist in increasing the recycling initiatives in Malaysia. The second consequence is the hardship to assess the scarce material's quantity that cause restriction for the usage of those materials. If a certain material usage is suddenly increasing, it will cause the restriction of material and increase the cost of material. The condition is getting serious when the mining of the material is monopolized by some countries. When the material cost is increase, the production cost will rise too. Hence, with the list of security material, consumer can reduce the demand of the material or use the material more efficiency.

There are some dimension and factors needed to conduct the assessment. The assessment needs to analyse the impact of materials and industrial in Malaysia. From that analysis, suitable criteria will find for develop the material security list and material security index for Malaysia.

1.3 Objective

The objectives of this study are:

a) To identify the critical material for Malaysian economy.
b) To model the important parameters for the critical materials
c) To assess the material security of the critical material.
d) To apply the product recycling desirability model for assessing the criticality of material for Malaysia.

1.4 Scope

This study is helps in determine the criticality of material for Malaysia. The case and scenario of the critical material study is based on the importance of Malaysia economy, and efficiency of raw material. The reason that selects the two elements is because contribution of raw material in mining and manufacturing is the driver of growth of Malaysia's manufacturing and mining sectors. While manufacturing sector is the main contribution to growth of Malaysia economy. The result can refer to report Economic, Monetary and Financial Developments in 2019 (Yunus, 2019) So, the range of this study is focus on material risk and material supply risk. The raw material groups include iron and ferro-alloy metals, non-ferrous metals, precious metals and industrial minerals.

1.5 Report Outline

This report is constructed from 5 chapters. Introduction is the first chapter, and this chapter discusses the context and background of the study and problems identified through research articles, journals, and reports. Then followed by objectives that can be achieved through the study and scope which narrows down the area of study.

The second chapter is Literature Review. This chapter covers the big pictures of the study and the basic theories of the study. Then continue with the other assessments regarding to the study and previous studies from journals, articles, books and the internet. Then the definition and the scope of this study is explained. Lastly, the assessment methods of the study are also described.

The third chapter is Methodology. This chapter discusses about the assessment of material security and criticality. This chapter shows the method to collect data and method to select elements and dimension for this project. This chapter describe the selected indicators and dimension in term of supply risk and economic importance.

The fourth chapter is Results and Discussions. This chapter analyses the information and data that collected from the material security assessment. Then the data collected was interpret in this chapter.

The fifth chapter is Conclusion and Recommendation which summarizes the development of material security for Malaysia assisting the Product Recycling Desirability Model.

CHAPTER 2

LITERATURE REVIEW

2.1 Circular Economy

A concept called circular economy is introduced and applied in order to create a prosperous environment for future generations. Circular economy is a concept that ensures the resources are kept in use for as long as possible, extracting the maximum value and then recovering and regenerating products and materials at the end of life (Mativenga et al., 2017). Circular economy also can define as regenerative system. The resource input and waste, emission and energy leakage are minimised. This situation can be achieved by process repair, reuse, remanufacture and recycle the end-of-life products. Circular economy is strongly recommend as a solution to global challenges and problems such as resource shortage, waste generation, etc (Geissdoerfer et al., 2017). There are several examples of research that related with circular economy shown in Table 2.1.

Table 2. 1 List of research that related with circular economy

Research	Project	Effort to apply circular economy
Jensen & Skelton (2018)	Wind turbine	• Design a wind turbine that can be re-use. • Resize the sectioning of the wind turbine blades that can use for secondary applications.

		- Using a 100% recyclable concrete rubble. - Convert the composite material into new materials for other purpose.
M. Andersson et al. (2019)	Vehicle and electric and electronic equipment	- Refine and recycle precious material from PCB.
Akcil et al. (2019)	LCD panel	- Recycle and extract element Indium (In) from waste LCD panel.
Wong et al. (2018); Cheng et al. (2012)	End of life vehicle (ELVs)	- Recycle waste vehicles.
Zhu et al., (2020)	PCB	- Using renewable collector to recover and recycle copper and ion from waste PCBs.
Mossali et al. (2020)	Lithium-Ion Batteries	- Develop a system that enable the batteries easy to be reused. - Minimized amount of materials to be landfill. - Recycle the valuable elements such as Cobalt, Nickel and Lithium.

2.2 Waste Issue and Challenge

Waste issue especially solid waste issue is becoming a serious problem in both small and large cities of developing countries. There are some scholars have identified the root causes of the solid waste problem. According to Abdel-shafy & Mansour (2018), the causes of the solid waste problem is increase in population, rapid urbanization, booming economy and rise in the standard of living.

There are many types of garbage wastes and most of them is recyclable material, which were plastic, paper, and metal. The types of wastes can divide into plastic waste, wood waste, electronic waste (E-waste), metal waste, industries solid waste etc. These solid wastes will cause a series of serious environmental problems. The study Abdel-shafy & Mansour (2018) shows that there are 50 million tons of plastic wastes were generated annually by Europe, Japan and USA. While in the Africa continent, there are estimated 4.4 million tons of mismanaged plastic waste in 2010 and it could be as high as 10.5 million tons in 2025 if no action is taken to solve the plastic waste problem (Jambeck et al., 2018). The plastic pollution will give a complex impact to environment such as deteriorates water resource quality, extinction of aquatic animal and worsen the aesthetic value of environment (Lestari & Trihadiningrum, 2019). For industry solid waste issue, according to (Liu et al., 2016), it mentions that the large amount of industries solid waste can release large amount of toxic particles and substances to the surrounding, such as acidic and alkaline water, heavy metal, dust, etc. The harmful and toxicity substances can affect the condition and situation of environment.

The waste issues are not only caused environment problem, the improper management of solid waste can also cause the reduction of available landfill site. Nowadays, the fastest and easiest way to manage the solid wastes or dispose wastes are send them to landfill site. From the data from Adam et al. (2020), there are only 2% of plastic wastes is recycled in Ghana (country in West Africa), while the remaining 98% of the wastes were disposed to landfill site or leak to sea. While in Europe, based on study Sauve & Van Acker (2020), there are 23% of wastes in EU was send to landfilling in 2017.

In recent years, the continuous technological innovation has triggered the growth of electric and electronic devices. At the same time, there are 47.7 million tons of electronic waste (E-waste) was generated in 2016. The data was collected from 10 selected countries, and the data is shown in Figure 2.1. Same with plastic waste, most of the E-waste was disposed into landfill site informally. In the US, there are almost 75% of E-waste was disposed in landfill site, this is a large amount of E-waste (Intrakamhaeng et al., 2020).

In Malaysia, landfilling was also one of the waste treatment method. There are almost 99% of solid waste management is done by landfilling. For Malaysia, most of the material and products in landfill site were automotive shredder residue (ASR). Furthermore, the disposal of tyres is also occupied the landfill spaces. The waste problem getting serious when the available landfill spaces are insufficient due to high dependency to landfilling (Aishah et al., 2013). This is because landfilling is the easiest and fastest way to dispose solid waste for current waste management. This behaviour can proof by Mativenga et al. (2017) and the data is shown in Table 2.2. The data was collected from 50 companies and most of the manufacturers and end users were preferred disposed the waste by landfill.

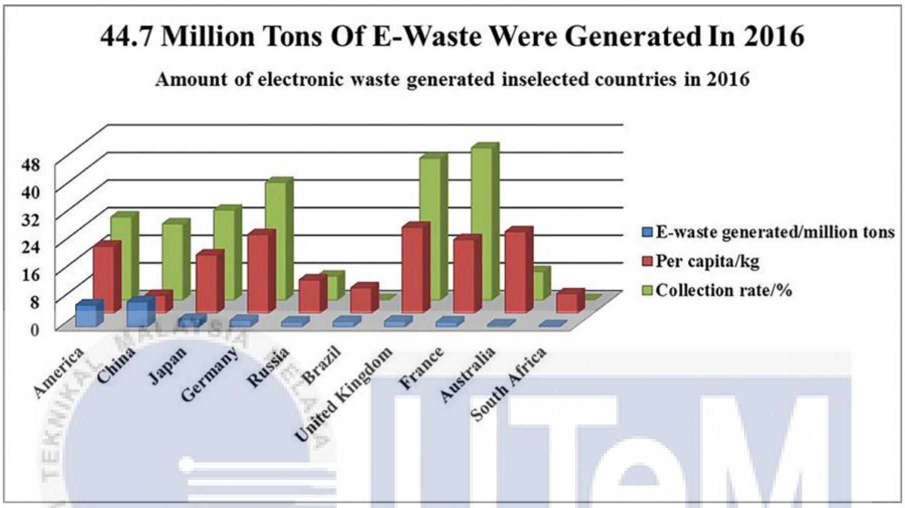


Figure 2.1 Data of electronic waste generated in 2016 (Intrakamhaeng et al., 2020).

Table 2. 2 Behaviour in manage composite waste (Mativenga et al., 2017)

	Landfill	**Re-use**	**Recycling**	**Incineration**	**I do not know**
Carbon fibre composite	8	1	2	1	1
Glass fibre composite	10	3	3	1	-
Resins	8	3	3	2	-
Dry fibres	8	4	3	2	1
Total	34	11	11	6	2
%	53	17	17	9	3

The function of landfill is not only use to keep the wastes, it also can control the leak of pollutants into sea (Intrakamhaeng et al., 2020). However, landfilling is not a long-term solution of solid waste and it will also bring certain environmental issues and problems such as changing the pH value of soil and mixing the toxic substances with soil. This situation will cause the hazardous diseases on human, animals and plants (Islam et al., 2020).

In Malaysia, the amount of E-waste is growth year by year in a rate 14 percent. Malaysia is produced around 1Million tonnes of E-waste per year and only 25% of the waste is recycling. While the rest of waste is worth RM3 Billion. This is happened because government or agencies are not provide the legislative framework in this case and manufacturers is not responsible to collect back the end-of-life products (Shumon and Ahmed, 2013). So, most of the E-waste was disposed to landfill and landfill is also the current Malaysia E-waste flow stream. The Figure 2.2 shows the flow model of E-waste from the source of generation until the area of disposal in Malaysia. This situation may cause the reduction of available landfill site and may waste some valuable material in end-of-life products.

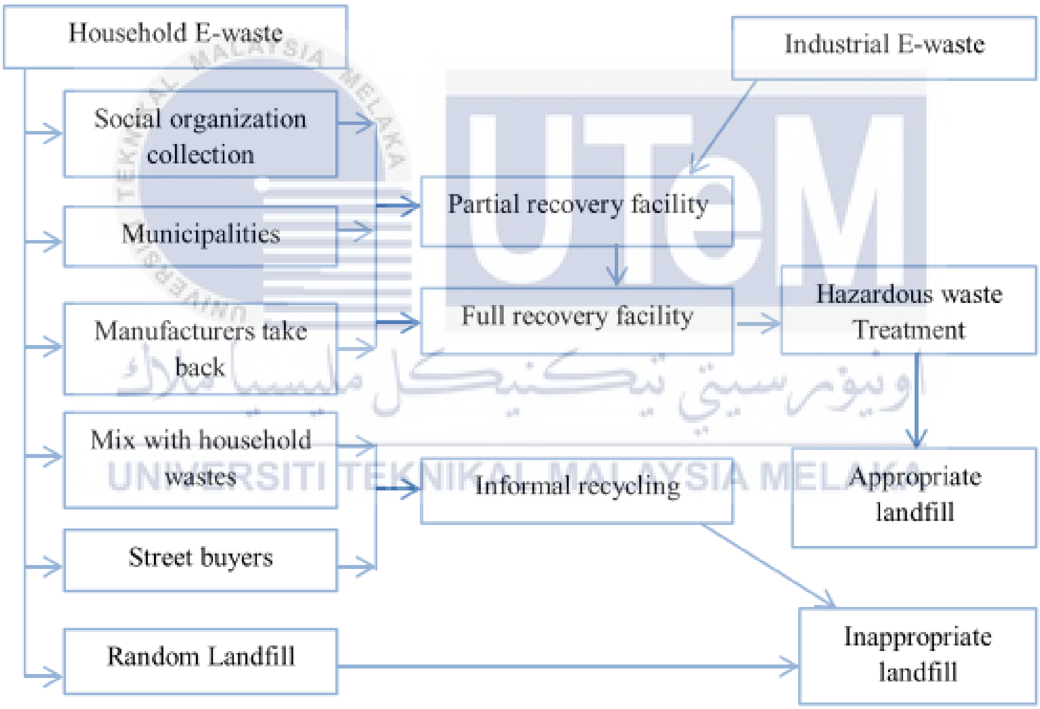


Figure 2. 2 Flow Model of E-waste in Malaysia products (Shumon & Ahmed, 2013).

2.2.1 Importance of recycling

The data in Table 2.1 shows that recycle process is one of the ways to implement concept of Circular Economy Model. Recycling is a process or method that collected the useable materials from wastes. There are a few studies show that recycling process can bring a bunch of advantages. Based on study (Ibanescu et al., 2018), the recycling of e-waste composition can benefit 3 sectors, which are economic, environmental and public health. From the perspective of economic, the Waste of Electric and Electronic Equipment (WEEE) contains a variety of useful materials including precious and valuable metals such as gold, silver, copper, aluminium, iron etc. While from the perspective of environmental, the recycling of E-waste can reduce and lower the pressure on the environmental. This is happened because certain raw materials are able to extract from mineral deposits. This idea can support by Laurenti et al. (2018). In the perspective of public health, the decrease of amount of WEEE will lower the risk to human health because WEEE contains varies hazardous substances that can harm human.

According to Ferronato et al. (2019), recycling behaviour has slow down the trend of financial crisis 2008 in Romania. This shows that recycling process have some impact on the growth of economy. This is because recycling process also can sustain the amount of scare material. The research Izumi (2004) has mentioned that recycling process can extract the scarce and valuable material from waste semiconductors and at the same time can reduce the generation of harmful and toxicity gases. The scarce materials include gallium and arsenic. Both of the material is critical and have listed on UK critical material list (Hollins, 2008). Besides that, recycling process can reduce the production cost for certain products. Based on study (Mossali et al., 2020), it says that recycling of lithium ion batteries can gain steel, copper, iron, graphite and also cobalt. At the same time, the recycling process can save the cost of batteries up to 13% (Sonoc et al., 2015). However, there are only 3% of LIBs are recycled in world.

While in the sector of automotive construction industries, the main components of end-of-life vehicles (ELV) are steel, aluminium, and cast iron and rubber. The materials from ELVs are recycled into new materials for manufacturing new vehicle or creating other products. This method can reduce the manufacturing cost and reduce the usage of landfill (Wong et al., 2018). Moreover, the rubber tyre can be recycled and reprocessed into many secondary products (Bott, 2014).

The other benefit from recycling process is reducing the mining and extraction process. In the growth of mobile and electronic technology, the demand of Rare Earth Elements (REE) is increasing in the last decades. The primary supply of REE is dominated and monopoly by China. The main supply of REE is highly depended on primary mining process. So, the REE is consider a valuable and precious material for current manufacturing sectors. The REEs were mostly used in electronic devices and it is able to extract from e-waste. This can found in the research Joseph et al. (2019), it mentions that the REEs can be extracted from e-waste. However, there are only 1% of the REEs was recycled and the other 99% was disposed to landfill site. In other words, the recycling of e-waste can obtain REEs. The research Joseph et al. (2019) has shown that Nd, Pr and Dy are able to extract from scrap magnet.

The Table 2.3 presents the potential recovery capacity of the 3 REEs from Malaysia HDD e-waste. It means that there are exceed 10,000kg of REE's are waste and not extract from end-of-life products. The value that can extract from the e-waste can exceed USD 500,000. So, the recycling from -waste can carry a bunch of advantages to economy and maximize the value of end-of-life product.

Table 2. 3 Potential recovery capacity of the REE's from Malaysia HDD e-waste.

Year	**Weight (kg)**		
	Nd	Pr	Dy
2018	8468	1228	508
2019	9171	1330	521
2020	9416	1365	565

2.3 Recycling Assessment

This topic discusses about the varies type of recycling assessment from other research papers. The assessments include life cycle assessment, recycling potential assessment, product recycling desirability model.

2.3.1 Life cycle assessment (LCA)

There are a few ways to conduct the assessment of recycling. The first model for recycling assessment is life cycle assessment (LCA). Figure 2.3 shows the LCA framework and the concept of LCA. The LCA defined as a material selection tool that is used to classify the material's environmental burden over its lifetime. This assessment is importance to manufacturer during the determination of applicability of recycled materials in the product design phase. This is because the LCA model can provide useful insights by generating insight into environmental 'pinch-to-point', savings opportunities and trade-offs for material selection, design and optimization. The study Tapper et al. (2020) has shown the method by using LCA framework for material selection for automotive materials and understand the applicability of material. There is another study, Klugmann-Radziemska & Kuczyńska-Łażewska (2020) shows that LCA can determine the environmental effects of recovering and recycling the valuable material such as REEs and PGMs. The study also used LCA model to evaluate the material behaviour and found that the re-use of recycled material had lower negative environmental impacts than primary material. Hence, LCA can help to do decision whether the product or material was suitable to be recycled or not.

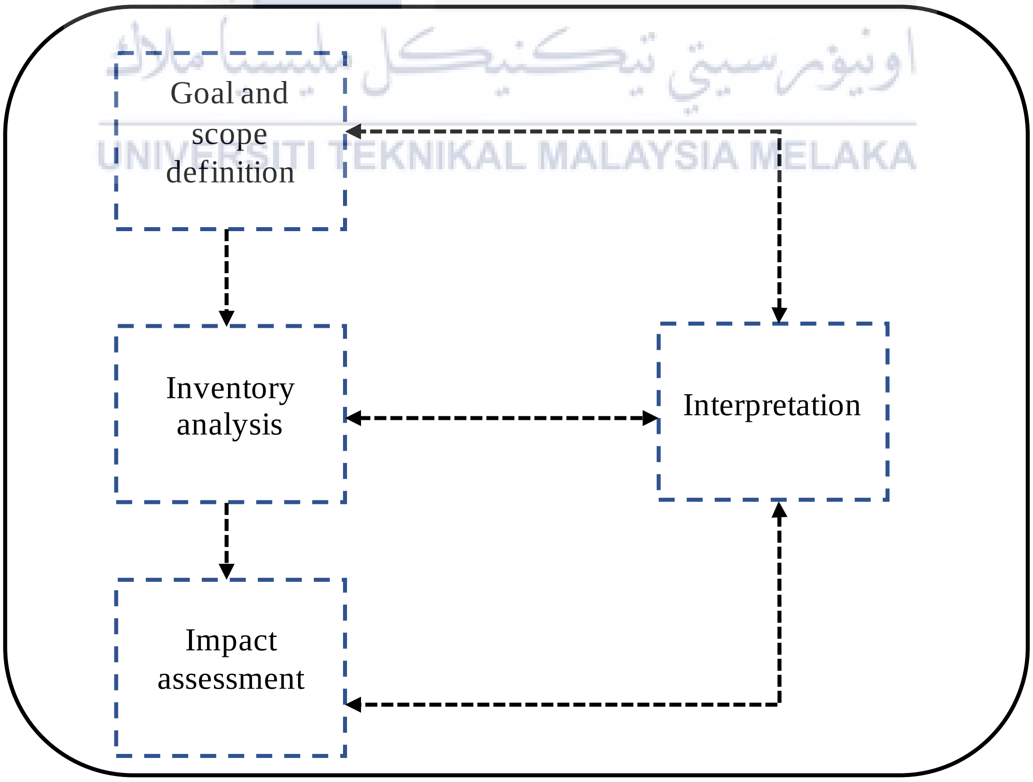


Figure 2. 3 LCA framework (Ouellet-Plamondon & Habert, 2015)

2.3.2 Recycling potential assessment (RPA)

The second model for recycling assessment is recycling potential assessment (RPA). The RPA model is applied to forecast the generation of wastes and calculate tonnages estimates that can be diverted from landfill through recycling, waste reduction and composting. The RPA is consisted of 4 modules which are waste generation, recycling tonnages, cost modules and reporting modules. The RPA model has encouraged the solid waste from disposal to recycle because it can bring varies advantages and benefits to environment. The RPA model had recommended a new waste prevention and recycling programs in the Seattle's 2011. The Table 2.4 shows the environmental value of recycled solid waste and the data is evaluated and calculated by RPA Model (Blackwell, 2013). It shows there is positive benefit and good environmental value for recycle the solid waste.

Table 2. 4 Environmental value of recycled solid waste (Blackwell, 2013).

Year	Climate Change	Human Health-Respiratory	Human Health-Toxics	Human Health-Carcinogens	Eutrophication	Acidification	Ecosystems Toxicity	Total Environmental Value
2010	26.4	9.0	31.3	0.3	0.0	1.2	3.0	71.5
2020	35.7	11.6	38.7	0.4	0.0	1.7	3.4	92.9
2030	39.0	12.6	41.7	0.4	0.0	1.9	3.8	101.0

2.3.3 Product Recycling Desirability Model

The third recycling assessing model is Product Recycling Desirability model. The model can be helped to identify and analyse the material recycling desirability index based on 3 different parameters. The parameters are complexity index, material security index (MSI) and technology readiness level (TRL). The Figure 2.4 shows the framework of the model. The model will evaluate and calculate the recycling desirability index of selected products. The Table 2.5 shows the products and its recycling desirability (Mohamed Sultan et al., 2017). From Table 2.5, the car battery had the highest value for total recycling desirability.

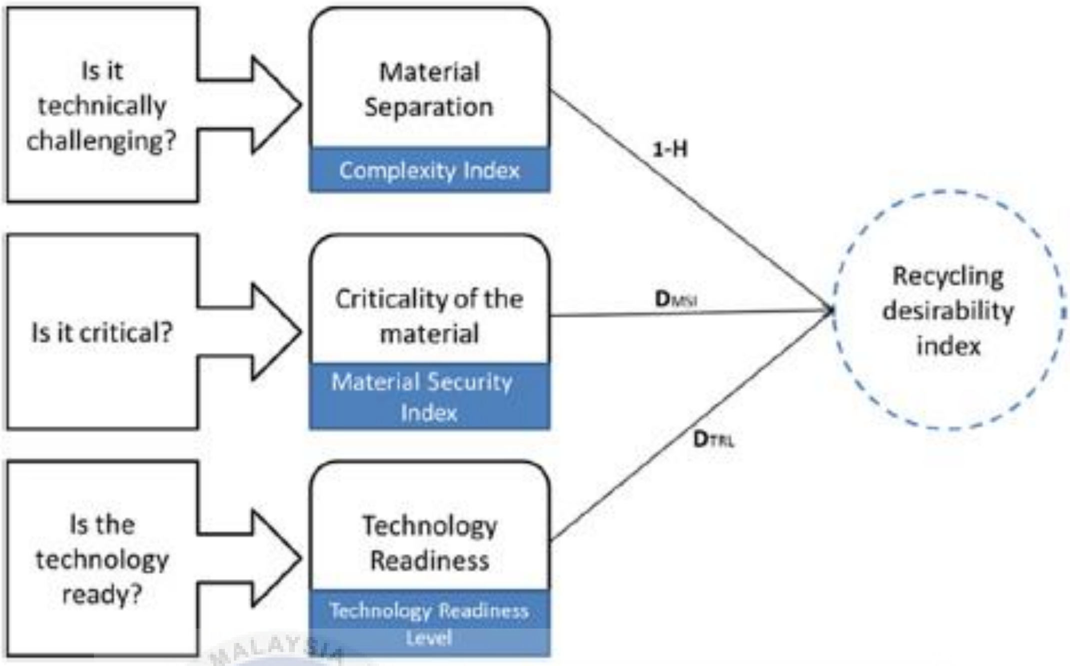
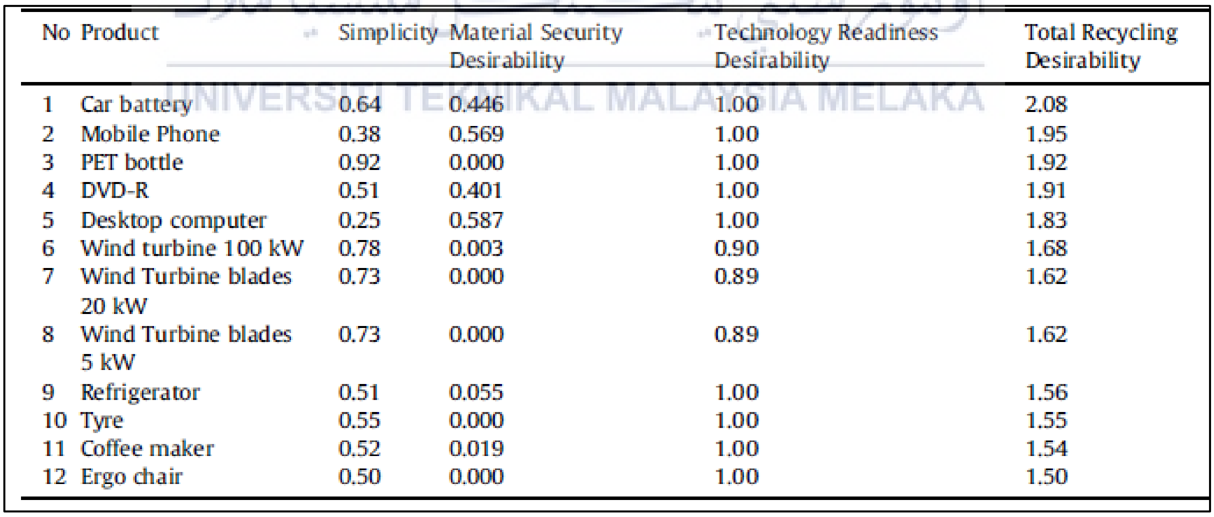


Figure 2. 4 Product Recycling Desirability (Mohamed Sultan et al., 2017).

Table 2. 5 Each product recycling desirability.



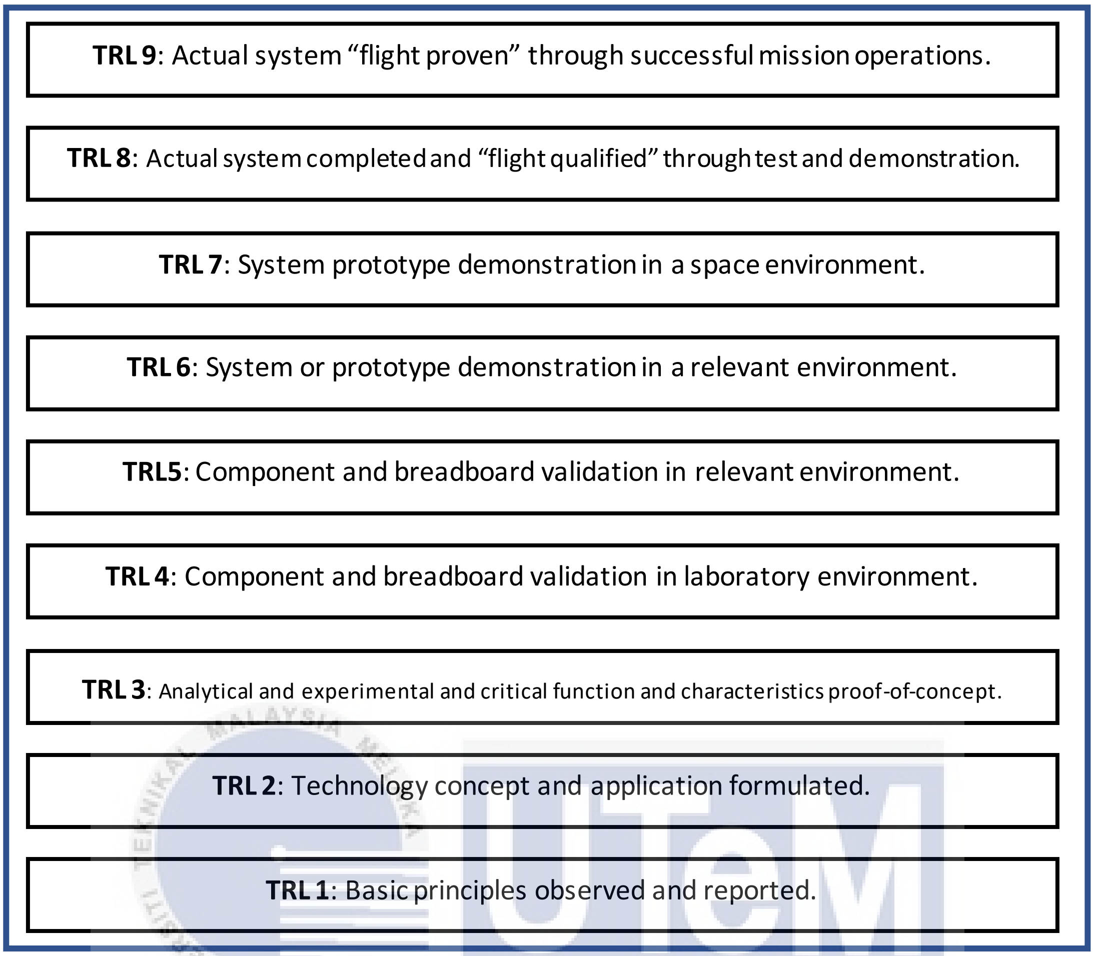
No	Product	Simplicity	Material Security Desirability	Technology Readiness Desirability	Total Recycling Desirability
1	Car battery	0.64	0.446	1.00	2.08
2	Mobile Phone	0.38	0.569	1.00	1.95
3	PET bottle	0.92	0.000	1.00	1.92
4	DVD-R	0.51	0.401	1.00	1.91
5	Desktop computer	0.25	0.587	1.00	1.83
6	Wind turbine 100 kW	0.78	0.003	0.90	1.68
7	Wind Turbine blades 20 kW	0.73	0.000	0.89	1.62
8	Wind Turbine blades 5 kW	0.73	0.000	0.89	1.62
9	Refrigerator	0.51	0.055	1.00	1.56
10	Tyre	0.55	0.000	1.00	1.55
11	Coffee maker	0.52	0.019	1.00	1.54
12	Ergo chair	0.50	0.000	1.00	1.50

2.3.3.1 Recycling desirability index

Product recycling desirability model is a model that used to evaluate whether a product is suitable for recycle. In other words, the model able to prioritise which product that is highly recommend for recycle process. The model is evaluated a product by calculate its recycling desirability index (RDI). The RDI is determined by different assessments and parameters. In the study (Mohamed Sultan et al., 2017), it shows a product recycle desirability model that using 3 different parameters. From the assessment, the 3 parameters are material security index (MSI), recycling technology readiness level (TRL), and Complexity index (Mohamed Sultan et al., 2017).

2.3.3.1.1 Technology readiness level (TRL)

Next parameter for Product Desirability Index is Technology Readiness Level. TRL is a measuring system that is used to assess the maturity level of a certain technology. The measurement system is developed at NASA on 1970s (Mai, 2017). There is total 9 TRL scale or level. TRL 1 is the lowest level and TRL 9 is highest level. The Figure 2.5 shows the information of TRL level from 1 to 9. Today, there are many studies have approach TRL to recycling process. For example, composites recycling technology, chemical recycling, and road recycling (Rybicka et al., 2016; Solis and Silveira, 2020; Troeger and Widyatmoko, 2012). The study Rybicka et al. (2016) shows the relationship between TRL and composites recycling technique in Figure 2.6.



TRL 9: Actual system “flight proven” through successful mission operations.

TRL 8: Actual system completed and “flight qualified” through test and demonstration.

TRL 7: System prototype demonstration in a space environment.

TRL 6: System or prototype demonstration in a relevant environment.

TRL5: Component and breadboard validation in relevant environment.

TRL 4: Component and breadboard validation in laboratory environment.

TRL 3: Analytical and experimental and critical function and characteristics proof-of-concept.

TRL 2: Technology concept and application formulated.

TRL 1: Basic principles observed and reported.

Figure 2. 5 The category of TRL level (Mai, 2017)

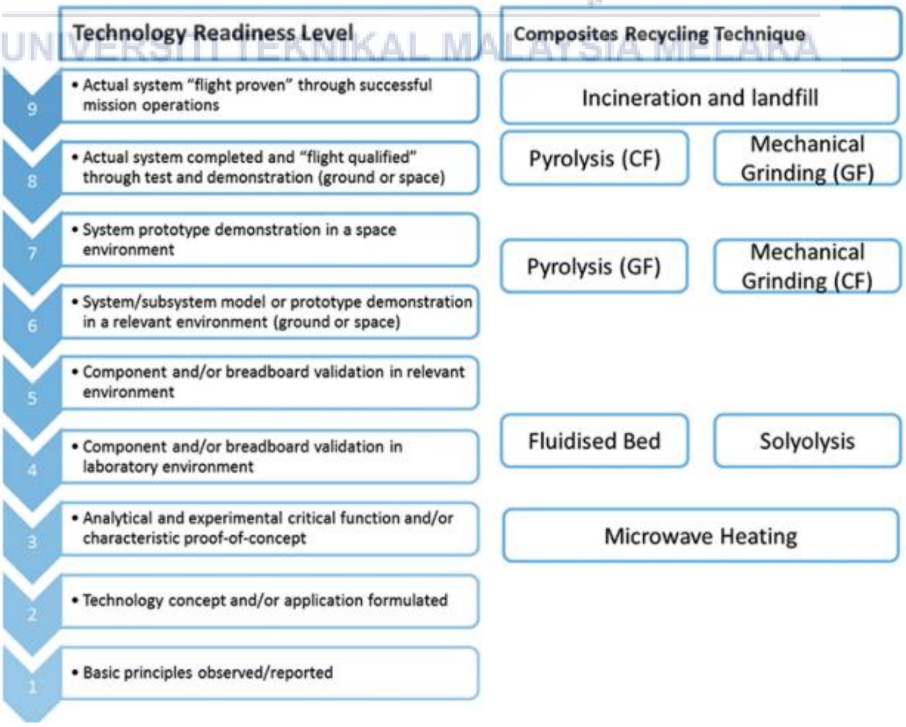


Figure 2. 6 Relationship between TRL and composite recycling technique (Rybicka et al., 2016).

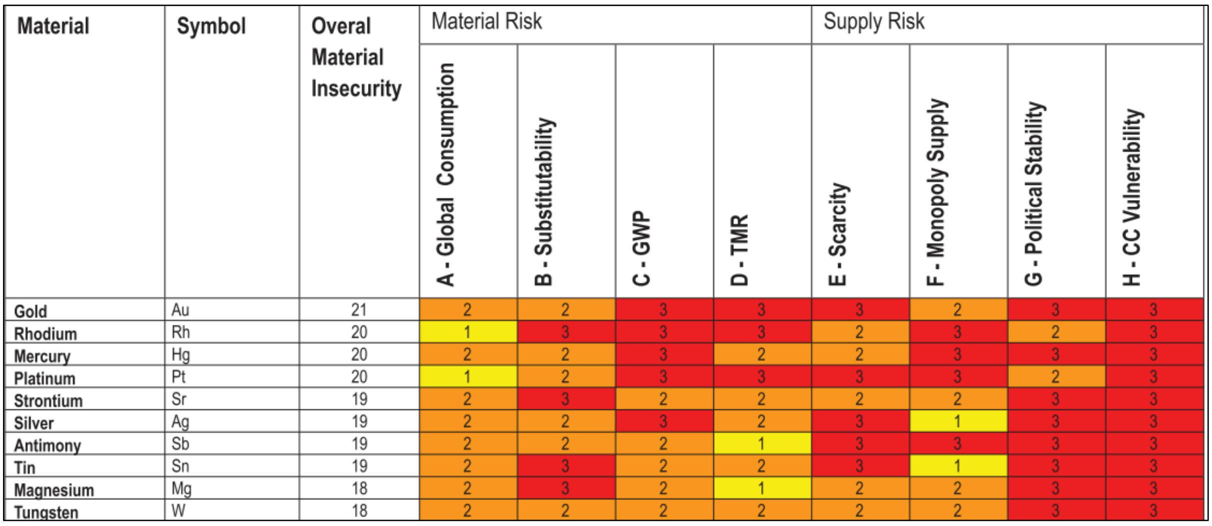
2.3.1.1.2 Complexity index

Next, complexity index is simplicity of a material to disassembly or separate to do recycle process. The study Mohamed Sultan et al. (2017) shows the way to calculate complexity index of material. The more complex the products, the higher the complex index.

2.3.3.1.3 Material security index

Material security index (MSI) is an index that is referring material security as baseline. Material security is defined as the importance of the material in different level like economy, environment, political, etc. In other perspective, material security has no disadvantage to economy or national defence due to restriction of certain material (Hollins, 2008). Material security is evaluate based on different parameters and the parameters is determine based on the importance of the country. For example, in UK, there are 69 insecure materials and the material security is rate by 8 parameters. The parameters are global consumption level, lack of substitutability, global warming potential, total material requirement, scarcity, monopoly supply, political instability and vulnerability to the effect of climate change. The Table 2.6 shows the top 10 insecure materials for UK (Hollins, 2008). The MSI is calculated based on the data from different dimensions and indicators. The study Mohamed Sultan et al. (2017) shows the steps to get the MSI in details. However, the insecure material list is only suitable for UK due to the parameters selected is based on UK economy. Therefore, there is needs for Malaysia to develop MSI to make the Product Recycling Desirability Model applicable.

Table 2. 6 Top 10 insecure material in UK (Hollins, 2008).



Material	Symbol	Overal Material Insecurity	Material Risk				Supply Risk			
			A - Global Consumption	B - Substitutability	C - GWP	D - TMR	E - Scarcity	F - Monopoly Supply	G - Political Stability	H - CC Vulnerability
Gold	Au	21	2	2	3	3	3	2	3	3
Rhodium	Rh	20	1	3	3	3	2	3	2	3
Mercury	Hg	20	2	2	3	2	2	3	3	3
Platinum	Pt	20	1	2	3	3	3	3	2	3
Strontium	Sr	19	2	3	2	2	2	2	3	3
Silver	Ag	19	2	2	3	2	3	1	3	3
Antimony	Sb	19	2	2	2	1	3	3	3	3
Tin	Sn	19	2	3	2	2	3	1	3	3
Magnesium	Mg	18	2	3	2	1	2	2	3	3
Tungsten	W	18	2	2	2	2	2	2	3	3

2.3.3.1.3.1 Definition of material security and scope

Recently, the concept of material security has conducted and evaluated by many researchers in several countries. This is because the increasing of raw material demand and at the same time rising of supply risks globally (Wang & Kara, 2019). In some research, the concept of material security is named as material criticality, mineral resources security, critical mineral, and securement of mineral resources (Graedel et al., 2012; Gupta et al., 2016; P. Andersson, 2020; Hatayama and Tahara, 2015). The assessment of material security can help the researchers to obtain a critical material list and information like role of raw material in economy.

The assessment of material security is conducted based on different indicators and dimensions selected. Table 2.7 is a compilation of studies providing a perspective on approach to material security research. The studies were collected from different countries such as UK, EU, India etc. The selection of objective and scope of study can be influenced and affected the result of materials criticality and security. A schematic diagram of overall flow chart of critical assessment is show in Figure 2.7. From the schematic diagram, it shows that the research goal and scope can influence the indicators selection and the selection of indicator is affected by availability of data. While the availability and quantity of data can influence the scoring of indicators.

Table 2. 7 Studies that have approach to concept of material security

Studies	**Year**	**Scope**
BGR (2006)	2006	Dispel concerns over raw material supply and assess long-term supply and demand.
Hollins (2008)	2008	Identify insecure materials that deserve attention.
Matthias Buchert, Doris Schüler (2009)	2009	Analysis on the availability and recycling potential of critical metals and propose course of actions.
DOE (2010)	2010	Assess opportunities and risks of key materials and develop critical material strategy.
Graedel et al. (2012)	2012	Design a criticality methodology that is helped corporate, national, and global stakeholders conduct risk evaluation and to inform utilization and strategic decision-making.
Parker (2013)	2013	Review and assess possible strategic to solve the issues of faced by UK manufacturing industry in the future as a result of possible raw material limitations of supply.
Achzet and Helbig (2013)	2013	Review on the differences and similarities of supply risk evaluation in different criticality assessment methods.
Miehe et al. (2016)	2016	Evaluate the systemic fundamentals of an operational model to measure resource criticality based on the diffusion curve of environmental issues at the business level.
Gupta et al. (2016)	2016	Assess the effect of critical minerals directly resulting from supply constraints on the manufacturing sector.

European Commission (2017)	2017	To establish a framework for the identification of critical raw materials and determine the critical raw material for EU.
Ferro & Bonollo (2019)	2019	Develop a framework to determine the criticality of materials.
Kim et al. (2019)	2019	Assess analytic hierarchy process (AHP) to secure a plausible weight for the appraisal of the raw material criticality in Korea.

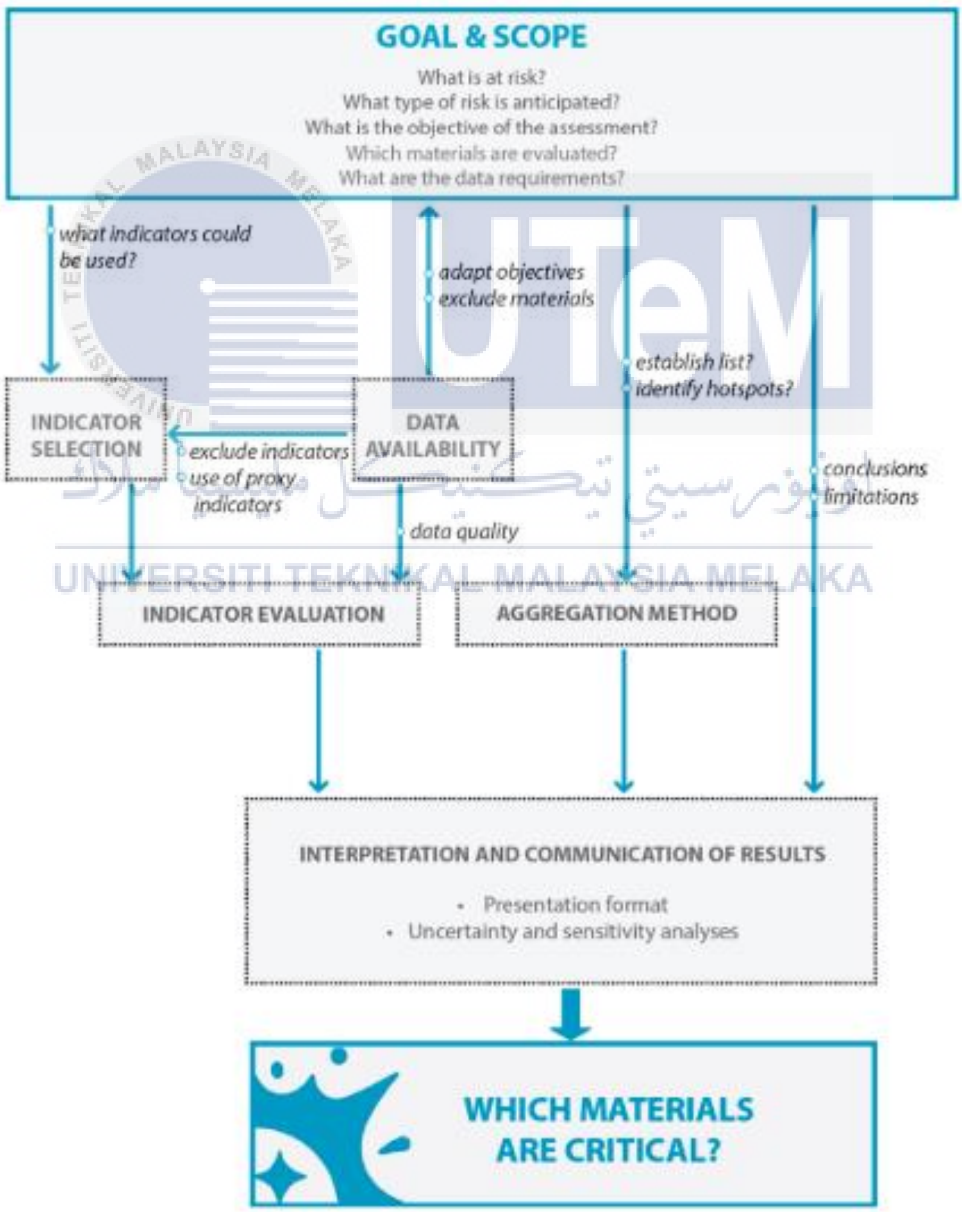


Figure 2. 7 Schematic diagram of critical assessment (Schrijvers et al., 2020)

2.3.3.1.3.2 Coverage of material security

Concept material security has grab attention by different world region recently and the concept is used to help the region to solve a problem, while the problem is related to security of supply of raw materials for the case of rare earths element. Each region has their own critical material list due to the criticality assessment method and scope is different. The assessment method of material security is depended on the selected dimensions and indicators.

According to study Barteková & Kemp (2016), it had shown the strategies for mitigating material security and criticality in the World such as China, The United State, Europe, Japan and Australia. The Table 2.8 shows the data of strategies for mitigating material security and material criticality in the World.

Table 2. 8 Strategies for mitigating material security in the World (Barteková & Kemp 2016)

Region		**Initiatives**	**Strategies**
China	• Resource rich • Dominant producer • Largest REEs supplier and consumer	• Increasing the competitiveness among local manufacturers. • Hold back REE for its domestic purpose. • Protect exploitation of REE. • Avoid restriction of REE in future. • Reducing availability of raw materials	• Declared REEE as protected and strategic materials. • Introduced several industrial policies to control the exploitation of REE. • Offers grants and loans to countries in exchange for access to their raw materials. • Implement concept circular economy (CE) as new economic model. • Apply 3R (Reduce, reuse and recycle) in production process.
US	• REE dominator on	• Assure materials availability for	• Devise policies targeting environmental.

	second half of 20th century. • REE goods manufacturer such as neodymium-iron-boron-magnetic powders.	national economic well-being. • Solve environmental problems. • Limited availability of REE. • Change in geopolitics in late 1980s. • China tightened its REE export quotas.	• Establish a list of critical materials to the US economy. • Establish an agency for maximising domestic mineral resource development and mitigating environment. • Provide funding for development of techniques which improve separation and decrease cost of processing REE. • Develop substitute materials and technology and eliminate the use of critical materials in certain industry. • Develop recovery and separation technology for REE from electronic waste.
Europe	• Resource poor • Low production of metallic minerals. • Highly import dependence on raw materials. • Low exploration and development on minerals.	• Maintaining access to sources of supply. • Insufficient data of availability of minerals. • Reduce the environmental impact of the industry. • Improve material and energy efficiency.	• Recycle the waste and substitute other materials to prevent shortage of certain materials. • Promote domestic exploration of raw materials. • Identify the most critical material and updating the mining inventory. • Focus on recycling projects and increase R&D in substitution.

	• Mainly REE sources is from finished good product.	• Sustain the supply of raw materials. • Decrease import dependence on raw materials.	• Develop policies in management of raw materials.
Japan	• Resource poor. • Highly dependent on import minerals. • Economy significant dependent on refining REE into metals and alloys. • REE products manufacturer. • Largest consumer of dysprosium (one of the REEs).	• Economic warfare during the World War 2. • Reduce import dependency on certain raw materials. • Sustain economic security. • Lowering the usage of REEs.	• Japan's government declared policies that support material exploration and development. • Focus on recycling and stockpiling of rare metals. • Improve resource security by increasing self-sufficiency by launched Strategic Energy Plan. • Recycling of scrap and end-of-life products. • R&D in recycling technology. • Collect end-of-life products and transform it into secondary supply of raw materials.
Australia	• Major minerals exporters. • Leader in extracting several raw materials	• Increase in metals price. • Increase international competitiveness. • Sustain the resources availability.	• Declared REEs as critical mineral due to high resource potential. • Provide information on sustainable mining practices to mine managers and others related departments.

	including REEs.	• Provide secure supply of REEs. • Increase investor confidence in resources sector. • Improve regulatory environment.	• Design a framework to support minerals development. • Develop methods to extract REEs with better energy efficiency.

2.3.3.1.3.3 List of critical material in varies countries

The Table 2.9 is the list of critical material from the United Kingdom, Europe, India, Japan, Russia, Australia and South Korea (Hollins, 2008; European Commission, 2017; Gupta et al., 2016; Hatayama & Tahara, 2015; Bortnikov et al., 2016; Skirrow et al., 2013). The similarity of those 7 critical material lists are all the lists contain REEs and platinum-group metals.

Table 2. 9 List of critical material from varies countries

Region / Material	UK	EU	India	Japan	Russia	Australia	South Korea	Total
Aluminium				√		√	√	3
Ammonia	√							1
Andalusite	√							1
Antimony	√	√				√	√	4
Arsenic	√					√		2
Asbestos	√							1
Barium	√					√		2
Baryte	√	√						2
Bentonite	√							1

Beryllium	√	√	√		√	√		5
Bismuth	√				√	√		3
Borate	√	√						2
Boron	√							1
Bromine	√							1
Cadmium					√	√		2
Cerium		√	√		√	√	√	5
Chromium	√		√	√		√	√	5
Cobalt	√	√		√	√	√	√	6
Copper	√			√		√	√	4
Diamonds	√							1
Diatomite	√							1
Dysprosium		√	√	√	√	√	√	6
Erbium		√	√		√	√	√	5
Europium	√	√	√		√	√	√	6
Feldspar	√							1
Fluorspar	√	√				√		3
Gadolinium	√	√	√		√	√	√	6
Gallium	√	√	√		√	√	√	6
Germanium	√	√			√	√		4
Gold	√			√		√		3
Graphite	√	√	√			√		4
Hafnium		√			√			2
Helium		√				√		2
Holmium	√	√	√		√	√		5
Indium	√	√		√	√	√	√	5
Iodine	√							1
Iridium		√				√	√	3
Iron	√			√		√		3
Kyanite	√							1
Lanthanum		√	√		√	√	√	5

Lead				√		√	√	3
Limestone			√					1
Lithium					√	√	√	3
Lutetium	√	√	√		√	√	√	6
Magnesium	√	√					√	3
Manganese				√		√		2
Mercury	√					√		2
Mica	√							1
Molybdenum	√			√		√	√	4
Natural rubber		√						1
Neodymium		√	√	√	√	√	√	6
Nickel	√			√		√	√	4
Niobium	√	√	√	√	√	√		6
Osmium	√					√	√	3
Palladium	√	√		√		√	√	5
Perlite	√							1
Phosphate rock		√						1
Phosphorus		√						1
Platinum	√	√		√		√	√	5
Praseodymium		√	√		√	√	√	5
Promethium					√	√	√	3
Rhenium	√		√		√	√		4
Rhodium	√	√		√				3
Ruthenium	√	√				√	√	4
Samarium		√	√		√	√	√	5
Scandium		√	√		√	√	√	5
Selenium	√				√	√	√	4
Silicon	√		√					2
Silicon metal		√						1
Silver	√			√		√		3
Soda ash	√							1

Strontium	√		√		√	√		4
Talc	√							1
Tantalum		√	√	√	√	√		5
Tellurium	√				√	√		3
Terbium	√	√	√		√	√	√	6
Thallium							√	1
Thorium						√		1
Thulium		√	√		√	√	√	5
Tin	√			√		√		3
Titanium					√	√	√	3
Tungsten	√	√		√		√	√	5
Uranium						√		1
Vanadium	√	√				√	√	4
Vermiculite	√							1
Ytterbium		√	√		√	√	√	5
Yttrium		√	√		√	√	√	5
Zinc	√			√		√	√	4
Zirconium	√		√			√	√	4

🟨 = Rare Earth Elements

🟩 = Platinum Group Metals

For the UK, the assessment of material security is identified by a framework that using material risk and supply risk as the dimension. Each dimension had total 4 criteria in material risk and 4 criteria in supply risk. The material risk criteria are global consumption levels, lack of substitutability, global warming potential and total material requirement. While the supply risks are scarcity, monopoly supply, political instability and vulnerability to the effects of climate change. With the list of critical material, UK able to develop the solutions for mitigating critical materials. For example, in the study Hollins (2008) mentioned that the use of substitution method is a long-term solution to material security. The substitution method is about discovering the substitutions for the certain material or element. Moreover, recycling and reuse can reduce the amounts of wastes. Reuse and recycle also can use to sustain the availability of critical materials especially REEs. So, UK using the list of critical material to identify the importance of materials and find solutions to reduce demand of valuable materials such as REEs.

For Europe, the list of critical material is getting from European Commission (2017). The assessment of material security and criticality is identify based on two dimensions, which are supply risk and economic importance. Europe have selected the critical materials from 78 individual materials and evaluate it (Devauze, 2017). The critical material list can help to stimulate the production of critical material in Europe by focusing on recycling activities and mining activities. In perspective of politic, the critical material list can used by the European Commission during negotiating the agreements, develop research and innovation actions. Moreover, the critical material list can help to implement the concept of Circular Economy in Europe and enhance its economy stability.

For India, the study Gupta et al. (2016) has provide the assessment of material criticality in India and the list of critical material and minerals in India. The assessment is conducted under agency Council on Energy, Environment and Water (CEEW). The framework adopted to identify material criticality is two dimensional (2-D matrix). The criteria and parameters used for the assessment are supply risk and economic importance. In the criticality matrix, the critical material can divide into 4 different level of criticality. The study contains the detail of 4 level of criticality. The list of critical material in India can trigger and promote R&D to enhance recyclability and find substitutes for critical materials. At the same time, the critical material list can help to reduce the environment impact that caused by mining and extraction process. The solutions for the environmental issue can be recycling from waste products, developing a technology that can recover secondary minerals from primary minerals.

For Japan, the critical material list is referred from study Hatayama & Tahara (2015). From the study, the criticality assessment is conducted to metal only. The criticality assessment is developed to analyse the country supply risk and vulnerability to supply restriction. There are total 22 metals are selected to do the assessment. For the criticality assessment, there are total 5 category used to evaluate the metals. The categories are supply risk, price risk, demand risk, recycling restriction and potential risk. The result from the research can help the country to plan a more efficient resource strategy to overcome global or nationwide issues.

2.3.3.1.3.4 Assessing material security

There are many ways and method to conduct material security and criticality assessment. The Table 2.10 is the research about material security and criticality assessment methods done by researchers from year 2007 to 2019. Most of the assessment adopt the criticality matrix as a framework. The main components in the criticality matrix are the key dimensions and indicators.

Table 2. 10 Research that approach to material criticality from year 2007 to 2019

Study	Year	Main dimensions	Main indicators	Aggregation	Framework
Frondel et al. (2007)	2007	Development of supply and demand	Vulnerability and supply risk	No aggregation	Not clear
Hollins (2008)	2008	Material risk and supply risk	Vulnerability and supply risk	Indicators equally aggregated.	2-D criticality matrix
NRC (2008)	2008	Supply risk and supply restriction impact	Vulnerability and supply risk	Individual aggregation algorithm	2-D criticality matrix

Pfleger et al. (2009)	2009	Quantitative and qualitative indicators	Vulnerability and supply risk.	Indicators unequally weighted and aggregated	2-D criticality matrix
Rosenau-Tornow et al. (2009)	2009	Supply risk	Vulnerability and supply risk	Equally weighted and aggregated	Not clear
DOE (2010)	2010	Impact of disruption to clean energy and supply risk	Vulnerability and supply risk	Indicators unequally weighted and aggregated.	2-D criticality matrix
Graedel et al. (2012)	2012	Vulnerability to supply disruption, supply risk and environmental implications	Vulnerability, supply risk, and environmental risk	Individual aggregation and unequally weighted	3-D criticality matrix
(European Commission (2017)	2017	Economic importance, supply risk and environmental risk	Vulnerability, supply risk and environmental risk	Individual aggregation and equally weighted	3-D criticality matrix
(Kolotzek et al. (2018)	2018	Supply risk, environmental impact, and social implications.	Supply risk, environmental risk, vulnerability	Equally weighted and aggregated	3-D criticality matrix

Song et al. (2019)	2019	Economic importance and supply risk	Supply risk and vulnerability	Unequally weighted and aggregated	2-D criticality matrix

2.3.3.1.1.4.1 Material criticality matrix

Based on Table 2.10, there are 2 types of criticality matrix that often used, which are 2-dimensional and 3-dimensional criticality matrix. The 2-D criticality matrix has only 2 axis, axis-x and axis-y while the 3-D criticality matrix has 3 axis, axis-x, axis-y, and axis-z. Figure 2.8 is the example of 2-D criticality matrix that developed by study NRC (2008). The dimensions used are supply risk (axis-x) and impact of supply restriction (axis-y). From the framework, it can determine the most critical materials. The area of ‘Region of Danger’ that appears in Figure 2.8 shows the most critical materials which is high supply risk and high impact of supply restriction.

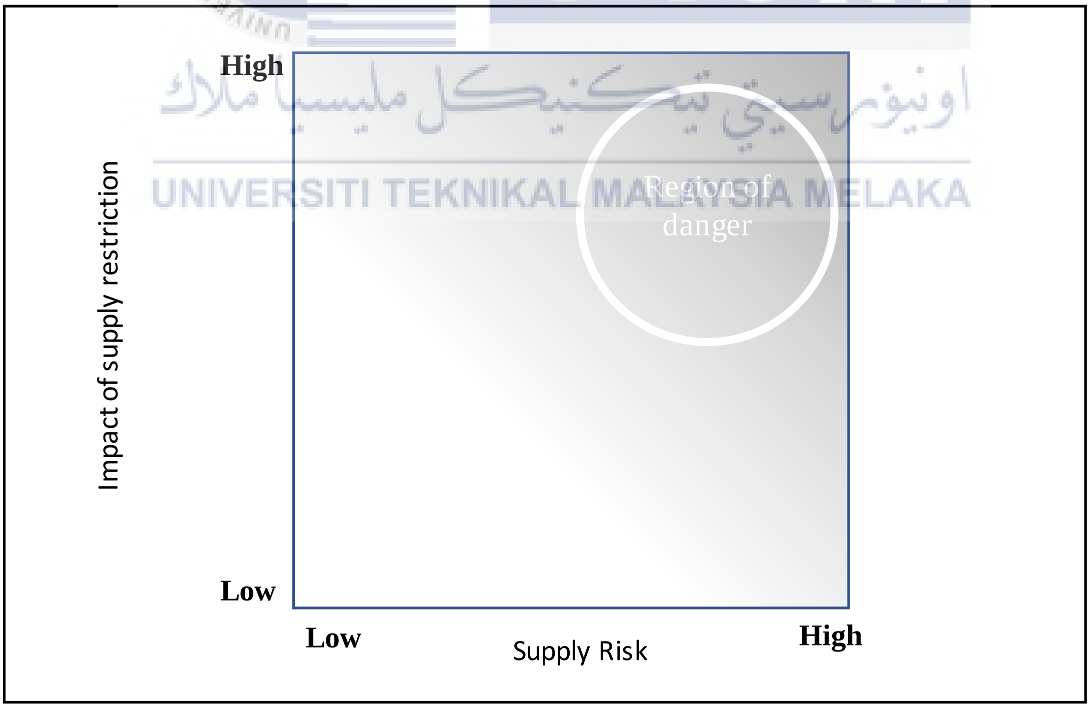


Figure 2. 8 The circled area is the highest material criticality (Erdmann & Graedel, 2011)

Next, the 3-D criticality matrix is introduced by Graedel et al. (2012) in 2012. The 3-D criticality has 3 different dimensions. In the study, the 3 dimensions used are supply risk, vulnerability to supply restriction and environmental implications. The material is classified as critical material when it has high supply risk, high vulnerability to supply restriction and high environmental implications. The Figure 2.9 shows the example of 3-D criticality matrix.

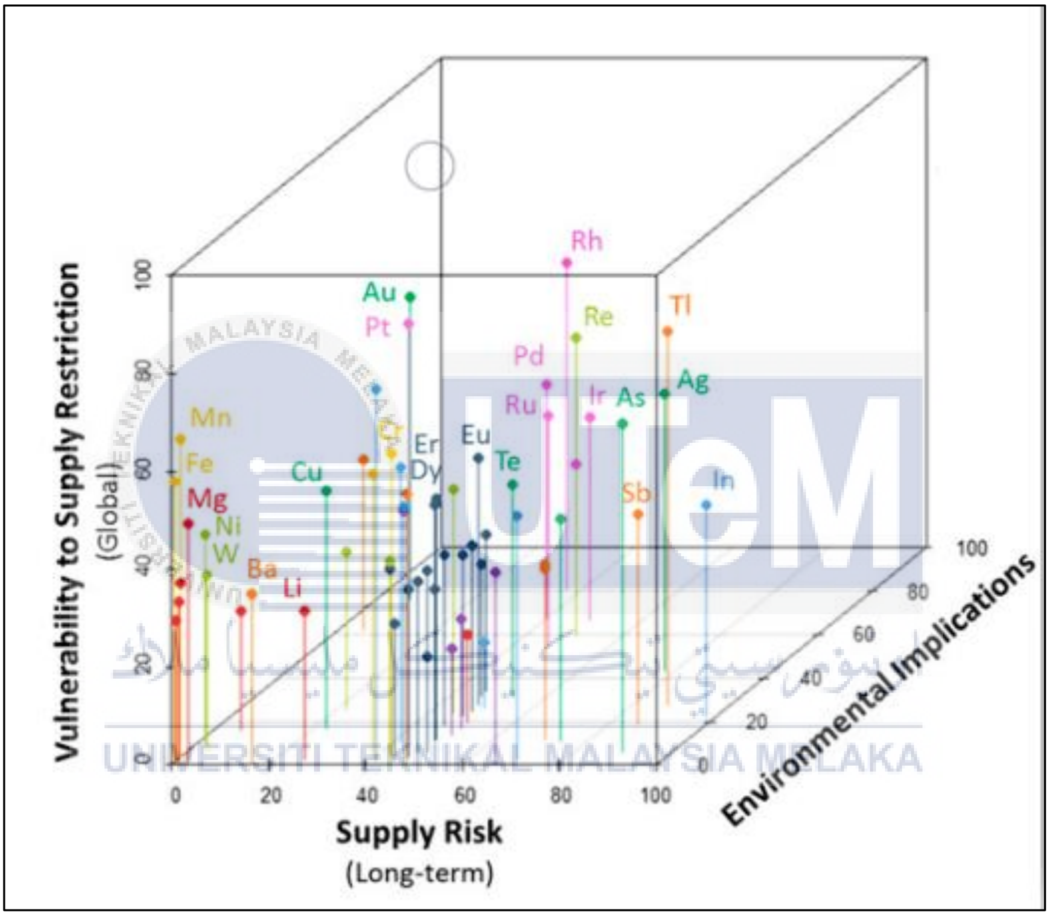


Figure 2. 9 The model of 3-D criticality matrix (Graedel et al., 2012)

2.3.3.1.3.4.2 Material security dimensions and indicators

In the assessment of material security and criticality, the parameters and dimensions used to develop list of material security is the important part. There are 13 dimensions criticality matrix is already used by current criticality assessments that show in Table 2.11. Among the 13 dimensions, the supply risk and vulnerability are the most frequent dimensions used by current researchers.

Table 2. 11 Review on dimensions used to determine material security

Study	SR	MR	VR	EI	ER	DE	MD	PR	DR	RS	EC	DG	PG
Behrendt et al., (2007)	√												
Frondel et al., (2007)	√										√		
Hollins (2008)	√	√											
NRC (2008)	√		√										
Rosenau-Tornow et al. (2009)	√												
Buchert et al. (2009)	√									√		√	
Marscheider-Weidemann et al. (2009)	√												
Pfleger et al. (2009)	√												
AEA Technology and Defra (2010)	√		√										
DOE (2010)	√		√			√							
Thomason et al.(2010)	√												
Erdmann & Graedel (2011)	√		√		√								
R. L. Moss et al. (2011)	√												

Parthemore, (2011)	√		√										
Gandenberger et al. (2012)	√		√										
Graedel et al. (2012)	√		√		√						√		
R. Moss et al., (2013)	√		√										
Goe & Gaustad, (2014)	√		√		√								
Roelich et al., (2014)	√		√										
(Simon et al., 2014)	√		√										
(Beylot & Villeneuve, 2015)			√										
(Hatayama & Tahara, 2015)	√		√		√			√	√	√	√		
Bortnikov et al. (2016)	√			√									
Gupta et al., (2016)	√			√									
European Commission (2017)	√		√	√	√						√		
McCullough & Nassar, (2017)	√						√						√
Kolotzek et al. (2018)	√				√								

Song et al. (2019)	√			√							√		
Total	27	1	14	4	6	1	1	1	1	2	5	1	1

SR= supply risk, MR= material risk, VR= vulnerability, EI= economic importance, ER= environmental risk, DE= Disruption to energy, MD= market dynamic, PR= Price risk, DR= demand risk, RS= recycling restriction, EC= ecological risk, DG= demand growth, PG= production growth

2.3.3.1.3.4.2.1 Supply risk

Supply risk is identifying and applying factors that can be used to assess the risk to the supply of a material. Moreover, supply risk can be used to define potential supply constraints of resources under consideration. Table 2.12 shows the supply risk indicators used by current studies.

Table 2. 12 Supply risk indicators used by studies

Indicators / Studies	Country concentration	Political stability	Scarcity	By-product dependency	Company /reserve concentration	Demand growth	Recyclability	Substitutability	Import dependency	Commodity prices	Exploration degree	Stockkeeping	Marketing balance	Mine/refinery capacity	Future market capacity	Investment in mining	Climate change vulnerability	Temporary scarcity	Risk of strategic use	Geopolitical risk
Behrendt et al., (2007)	√		√							√										
Frondel et al., (2007)	√	√							√											
NRC (2008)			√	√			√		√											
Hollins (2008)	√	√															√			
(Buchert et al., 2009)	√		√	√																
(Pfleger et al. (2009)	√	√	√		√	√		√											√	

Rosenau-Tornow et al. (2009)	√	√	√		√						√	√	√	√	√	√				
DOE (2010)	√	√	√	√	√	√														
Thomason et al. (2010)									√											
Erdmann and Graedel (2011)	√	√	√	√	√		√											√		
R. L. Moss et al (2011)	√	√		√		√														
Graedel et al. (2012)	√	√	√	√																
Hatayama and Tahara (2015)			√		√				√		√									
Gupta, Biswas, and Ganean (2016)	√						√	√	√											√
European Commission (2017)	√	√					√	√												
McCullough and Nassar (2017)	√													√						
Kolotzek et al. (2018)	√	√			√		√	√												
Song et al. (2019)	√	🟩																		
Total	15	11	9	6	6	3	5	4	5	1	2	1	1	2	1	1	1	1	1	1

The country concentration, also called as monopoly supply is the most indicators used as supply risk indicators. Monopoly supply means a certain material was concentrated only in one or two countries in the production of a certain material. This may cause future supply vulnerability. Monopoly supply conditions are becoming more worrying when concentrations of the materials or resource occur in less stable region (Lloyd et al., 2012). The score of monopoly supply is evaluate based on percentage of material concentration in any one region.

The second most indicator for supply risk is political stability. There is total 11 research using political stability in the determination of supply risk. This is because material suppliers can influence and interrupt by wars, famines, and other matters. The assessment and data about world political stability can get from World Bank's website (Daniel Kaufmann, n.d.). In this case, the higher the political stability for the material, the lower the score given.

Material scarcity is also frequent used as indicators for supply risk. This is because the root cause of scarcity of material is the depletion of the material. The scarcity of material may be temporary because it depends on the technology and cost available. In the study, the scarcity of material is ranked by amount reserves by 2050. The material is considered high scarcity when it is expected to exceed its reserves.

2.3.3.1.3.4.2.2 Vulnerability

Vulnerability also known as material risk. Material risk is described as potential damage caused by an involuntarily reduce utilization of a material. Table 2.13 shows the vulnerability indicators used by current studies.

The substitutability is the most frequent used indicators for vulnerability from Table 2.13. Material substitutability is the availability of a material in a production or system replace by another material. High substitutability can be explained by a common material capable of replacing a rare material with the same function and performance. In the scoring system, the lower the substitutability, the higher the score given.

In the four studies, the value of the products affected is used as an indicator for vulnerability. This indicator evaluates the potential harm of a resource's total supply disruption, taking into account only the occurrence of each material in a product but not the quantity (Helbig et al., 2016).

In 4 out of 14 studies, as an indicator for vulnerability, the ratio between future demand and current or recent supply is used. The value for this indicator is based on future prospects and not on present or pervious data. For a national economy strategy, this indicator can be considered as more important than handling supply disruptions of existing technology and widely utilized materials. In some studies, the future demand to supply ratio also used as indicator for supply risk (Kavlak et al., 2015).

Table 2. 13 Vulnerability indicators used by studies

Indicators / Studies	Substitutability	Value of products affected	Future demand to supply ratio	Strategic importance	Value of utilized material	Spread of utilization	Ability to pass thru cost increases	Change in demand share	Import dependency	Target group’ s share	Ability to innovate	Change in imports	Company concentration	Consumption volume	Mine production change	Price sensitivity	Primary material price	Recyclability
NRC (2008)	√		√		√													
AEA Technology and Defra, (2010)	√													√				
DOE (2010)	√					√												
Erdmann & Graedel, (2011)	√		√			√		√		√		√						
Parthemore, (2011)	√		√	√					√				√					√
Gandenberger et al., (2012)	√	√																
Graedel et al. (2012)	√				√	√			√		√							
R. Moss et al., (2013)			√															
Goe & Gaustad, (2014)		√		√													√	
Roelich et al., (2014)				√												√		
Simon et al., (2014)				√														
Beylot & Villeneuve, (2015)		√																
Hatayama & Tahara, (2015)								√							√			
European Commission (2017)		√																
Total	7	4	4	4	2	3	0	2	2	1	1	1	1	1	1	1	1	1

CHAPTER 3

METHODOLOGY

This chapter discusses about the assessment method of material security. There are 4 phases in conducting material security. The first phase is identified the framework used to determine material security. The second phase is determined the dimensions and its indicators that suitable for the assessment of material security for Malaysia. The third phase is developed a scoring system for evaluate the selected material based on the selected dimensions and indicators. The fourth phase is interpreted the result.

3.1 Research Methodology

The research consists of 4 main phase which are phase 1, selecting a suitable criticality matrix and material list. Phase 2, identified dimensions and indicators for the assessment, Phase 3 is developed a scoring matrix, and lastly Phase 4 is analysed and interpreted the data. The summary of the research methodology is shows in Figure 3.1.

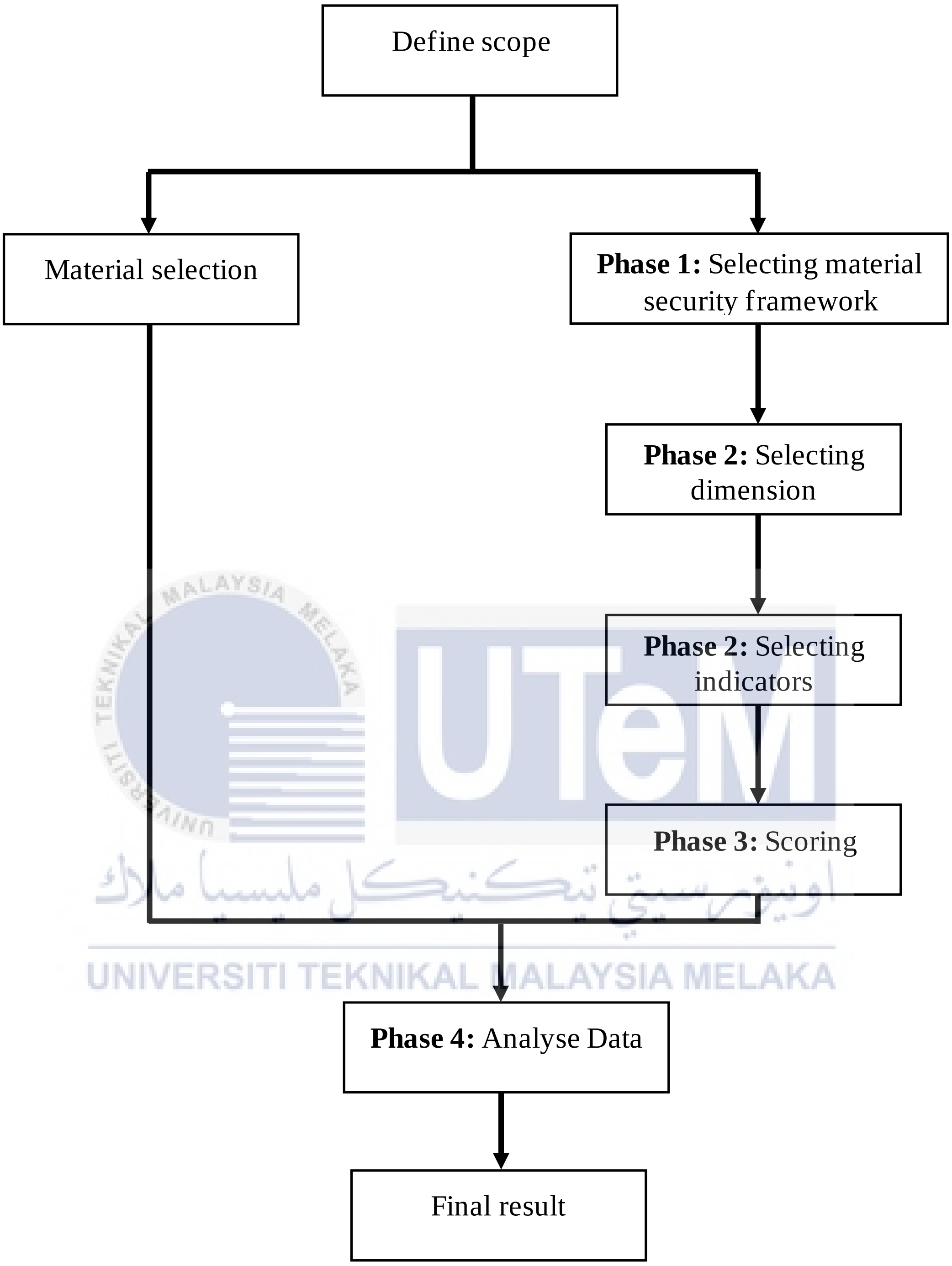


Figure 3. 1 Research methodology Flow chart

The first step of this assessment is defined the scope of the project. The scope of the project is focus on how material can influence Malaysia economy. The second step is material criticality matrix selection. For the selection of material criticality matrix, the content and elements for the matrix is refer to previous research and studies. The third step and fourth step are determined the dimensions and indicators used for this project. The selected parameters will show the important of critical materials. The dimensions and indicators selected is referred to others research and studies. The fifth step is developed a scoring matrix. The scoring matrix is used to evaluate the material criticality. The seventh step is conduct analysis on selected material based on the scoring matrix and plot the material on the criticality matrix graph. Lastly, the database of material security for Malaysia will generate and able to apply on Product Recycling Desirability Model. While for material selection stage, the material is selected from the referring to Malaysia Mineral and Geoscience Report.

3.2 Phase 1: Selecting Material Security Framework

There are various types of frameworks developed and used by several researchers for the evaluation and assessment of material security. One of the most well-known framework is material security matrix. In the previous chapter has already explain the material security matrix. For this project, the framework selected is 2-D material security matrix. This framework is also used by NRC (2008), Devauze (2017) and Erdmann & Graedel (2011). The Figure 3.2 is the draft for 2-D material criticality matrix.

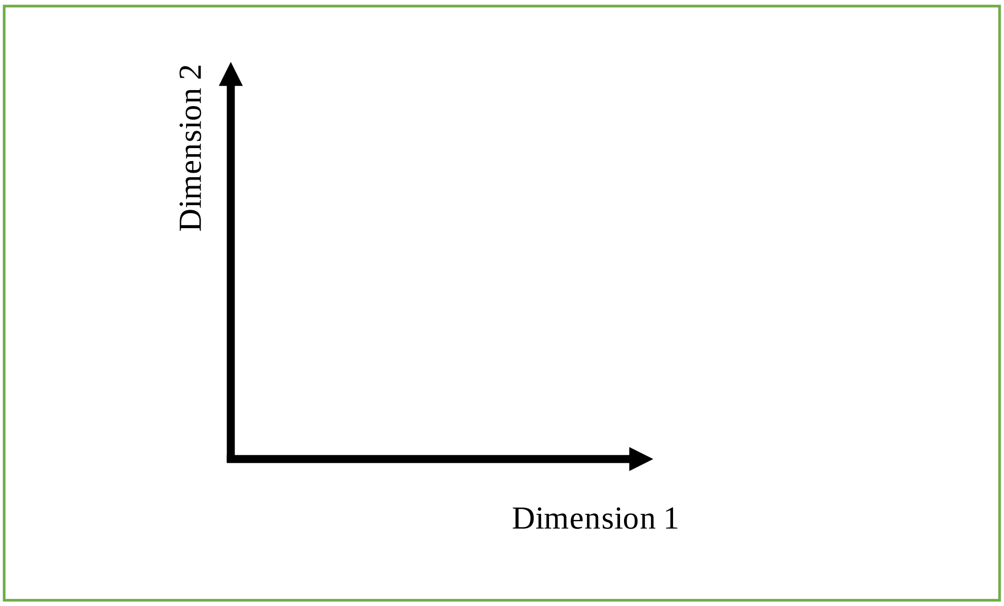


Figure 3. 2 Draft for 2-D material security matrix

3.3 Phase 2: Selecting Dimensions and Indicators

There are 2 dimensions needed to conduct the material security by using 2-D material security matrix. Each dimension has its indicators that help to evaluate material security and criticality. The 2 selected dimensions are supply risk and material risk. According to current Malaysia manufacturing and economy situation, Malaysia is a developing country. The contribution of manufacturing and mining for Malaysia economy is important. Which are around 22% of economy growth is contributed by manufacturing and 7% from mining. The biggest manufacturing sector is E&E industries and the growth of E&E can increase the demand of precious material like REE's material and platinum's group metals. Figure 3.3 shows the model diagram used to determine and evaluate material security database for this project. There is total eight indicators used in this material security assessment, which is scarcity, monopoly supply, political stability, climate change to vulnerability, Malaysia consumption level, substitutability, global warming potential and total material requirements.

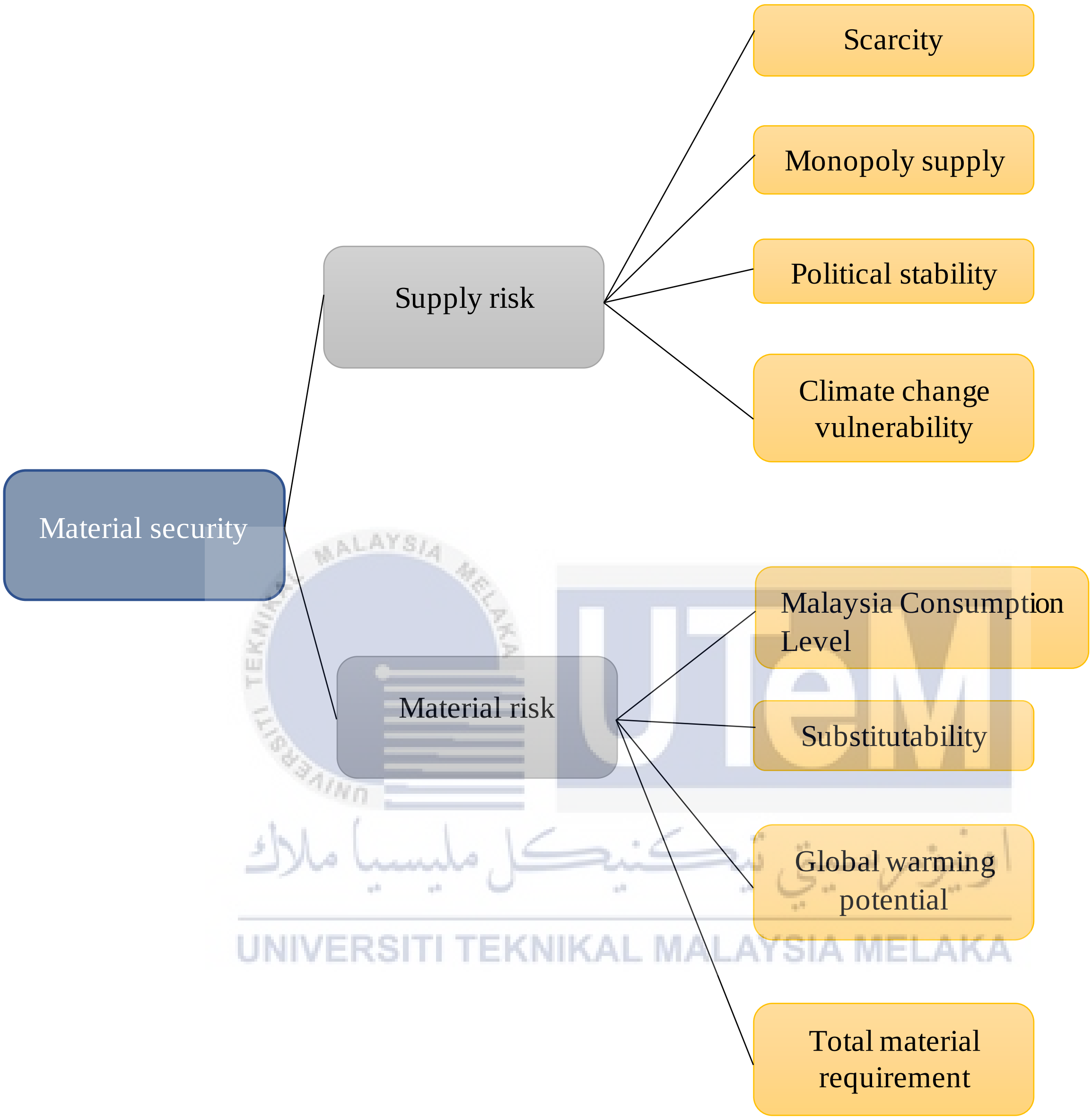


Figure 3. 3 Model Diagram for material security

3.4 Phase 3: Scoring

The scoring matrix to evaluate material security of Malaysia is referring to Devauze (2017), Hollins (2008) and Graedel et al. (2012). The Table 3.1 shows the scoring matrix that used to determine score of material. From the scoring matrix, the higher the score, the higher the material security and criticality.

Table 3. 1 Scoring matrix

Dimension		Supply risk (SR)				Material Risk (MR)			
Indicator/ criteria		Scarcity	Monopoly Supply	Political instability	Vulnerability to climate change	Malaysia consumption level	Substitutability	Global warming potential	Total material requirement
Score	1	not predicted to reach reserves by 2050	Concentration less than 33.3% in any one country	Political Stability Percentile greater than 66.6%	More than 51 climate risk index	Less than 1000 tonnes/yr	High	Less than 1kg CO2 per kg material extracted	Less than 100 tonnes/tonne mineral
	2	predicted to overrun reserves by 2050	Concentration between 33.3% - 66.6% in any one country	Political Stability Percentile between 33.3% - 66.6%	21-50 climate risk index	Between 1000 and 1000000 tonnes/yr	Data not available	Between 1 and 100kg CO2 per kg material extracted	Between 100 to 10000 tonnes/tonne mineral
	3	predicted to overrun reserve base by 2050	Concentration greater than 66.6% in any one country	Political Stability Percentile less than 33.3%	1-20 climate risk index	More than 1000000 tonnes/yr	Low	More than 100kg CO2 per kg material extracted	More than 1000 tonnes/tonne mineral

*Data not available for particular material will given score of 2.

3.5 Phase 4: Analyse Data

In this phase, the data is analyse based on the scoring matrix. The result of this phase is the result of the project. Each selected material will obtain a score for each dimension and indicator that evaluated through the scoring matrix. Then the material will plot on the graph of the material security matrix by using software MATLAB R2014b. From the material security matrix, the most insecure and critical material located on the top right of the material security matrix. Then the result from this assessment will compare with result from other countries to make comparison. After having the material security database, then apply the material security into Product Recycling Desirability Model to determine product recycling desirability index of selected products such as car battery, smartphone, DVD-R, etc. Then sketch the product distribution graph by using input from Product Recycling Desirability Model. The product distribution graph is sketched by Microsoft Excel. The function of the distribution graph is an analysis method to prioritize the products for recycling.

3.6 Material Selection

In material selection, the materials are selected from two sources. The first source is from Malaysia Mineral Yearbook 2013. In the mineral yearbook, it contains varies information of material in Malaysia such as operating mines in Malaysia, materials annual production in global and local, materials price, and amount of material in import and export. The information and data in the mineral yearbook can make the result in scoring process accurately. The second source of material selection is from the comparison with the list from other region such as UK, US, India, Japan, EU, and Australia.

CHAPTER 4

RESULTS AND DICSUSSIONS

This chapter discussed the data collected after completing the scoring process to all selected materials. All the discussions will be stated and compared the result from previous researches done by other researchers on the material security and product recycling desirability.

4.1 Database of Material Security

The main outcome of this project is the database of material security for Malaysia. The database shows the criticality of each selected material. The Table 4.1 shows the list of critical material for this project and there is total 89 materials are evaluated with 8 different indicators.

Table 4. 1 List of critical material

Material	Symbol	Supply Risk				Total	Material risk				Total	
		Scarcity	Monopoly Supply	Political Stability	Vulnerability to Climate Change	**Supply Risk**	Malaysia’s Consumption level	Substitutability	Global Warming Potential	Total Material Requirements	**Material Risk**	Total Material Criticality
Palladium	Pd	3	2	2	2	9	2	2	3	3	10	19
Rhodium	Rh	2	2	2	2	8	2	3	3	3	11	19
Gold	Au	3	1	2	2	8	3	1	3	3	10	18
Platinum	Pt	3	2	2	2	9	2	1	3	3	9	18
Tellurium	Te	2	2	2	2	8	2	3	2	3	10	18
Ammonia	NH3	2	2	2	2	8	2	3	2	2	9	17
Bromine	Br	2	2	2	2	8	2	3	2	2	9	17
Indium	In	3	2	2	2	9	2	1	3	2	8	17
Molybdenum	Mo	2	2	2	2	8	2	3	2	2	9	17
Niobium	Nb	2	3	3	1	9	1	3	2	2	8	17
Osmium	Os	2	2	2	2	8	2	2	2	3	9	17
Phosphate rock		2	2	2	2	8	2	3	2	2	9	17
Ruthenium	Ru	2	2	2	2	8	2	3	2	2	9	17
Strontium	Sr	2	2	2	2	8	2	3	2	2	9	17
Thallium	Tl	2	2	2	2	8	2	3	2	2	9	17
Yttrium	Y	2	2	2	2	8	2	3	2	2	9	17
Andalusite		2	2	2	2	8	2	2	2	2	8	16
Barium	Ba	2	2	2	2	8	2	2	2	2	8	16
Baryte	$BaSO_4$	2	2	2	2	8	1	3	2	2	8	16
Borate	BO3	2	2	2	2	8	2	2	2	2	8	16
Cerium	Ce	2	2	2	2	8	2	2	2	2	8	16
Dysprosium	Dy	2	2	2	2	8	2	2	2	2	8	16
Erbium	Er	2	2	2	2	8	2	2	2	2	8	16
Europium	Eu	2	2	2	2	8	2	2	2	2	8	16
Fluorspar		2	2	2	2	8	2	3	1	2	8	16
Gadolinium	Gd	2	2	2	2	8	2	2	2	2	8	16
Gallium	Ga	2	2	2	2	8	2	1	3	2	8	16
Hafnium	Hf	2	2	2	2	8	2	2	2	2	8	16
Helium	He	2	2	2	2	8	2	2	2	2	8	16
Holmium	Ho	2	2	2	2	8	2	2	2	2	8	16
Iodine	I	2	2	2	2	8	2	2	2	2	8	16

Iridium	Ir	2	2	2	2	8	2	2	2	2	8	16
Lanthanum	La	2	2	2	2	8	2	2	2	2	8	16
Lutetium	Lu	2	2	2	2	8	2	2	2	2	8	16
Mercury		2	2	2	2	8	2	1	3	2	8	16
Natural rubber		2	2	2	2	8	2	2	2	2	8	16
Neodymium	Nd	2	2	2	2	8	2	2	2	2	8	16
Nickel	Ni	3	2	2	2	9	2	1	2	2	7	16
Praseodymium	Pr	2	2	2	2	8	2	2	2	2	8	16
Promethium	Pm	2	2	2	2	8	2	2	2	2	8	16
Samarium	Sm	2	2	2	2	8	2	2	2	2	8	16
Silicon metal		2	2	2	2	8	2	2	2	2	8	16
Tantalum	Ta	2	1	2	1	6	3	3	2	2	10	16
Terbium	Tb	2	2	2	2	8	2	2	2	2	8	16
Thulium	Tm	2	2	2	2	8	2	2	2	2	8	16
Tin	Sn	3	2	2	2	9	2	1	2	2	7	16
Uranium	U	2	2	2	2	8	2	2	2	2	8	16
Ytterbium	Yb	2	2	2	2	8	2	2	2	2	8	16
Aluminium	Al	2	2	2	2	8	2	1	2	2	7	15
Antimony	Sb	3	2	2	2	9	2	1	2	1	6	15
Asbestos		2	2	2	2	8	2	1	2	2	7	15
Bentonite		2	2	2	2	8	2	2	1	2	7	15
Beryllium	Be	2	2	2	2	8	2	1	2	2	7	15
Bismuth	Bi	2	2	2	2	8	2	1	2	2	7	15
Cadmium	Cd	2	2	2	2	8	2	1	2	2	7	15
Chromium	Cr	1	2	2	2	7	2	3	2	1	8	15
Cobalt	Co	2	2	2	2	8	2	1	2	2	7	15
Diamonds (unit in carat)		2	2	2	2	8	2	1	2	2	7	15
Diatomite		2	2	2	2	8	2	1	2	2	7	15
Germanium	Ge	2	2	2	2	8	2	1	2	2	7	15
Graphite	C	2	2	2	2	8	2	2	1	2	7	15
Kyanite		2	2	2	2	8	2	1	2	2	7	15
Lead	Pb	3	2	2	2	9	2	1	1	2	6	15
Lime		2	2	2	2	8	1	2	2	2	7	15
Lithium	Li	2	2	2	2	8	2	1	2	2	7	15
Mica		2	2	2	2	8	2	1	2	2	7	15
Rhenium	Re	2	2	2	2	8	2	1	2	2	7	15
Scandium	Sc	2	2	2	2	8	2	1	2	2	7	15
Silver	Ag	3	1	3	1	8	1	1	3	2	7	15
Soda ash		2	2	2	2	8	2	1	2	2	7	15
Talc		2	2	2	2	8	2	1	2	2	7	15
Thorium	Th	2	2	2	2	8	2	1	2	2	7	15
Tungsten	W	2	2	2	2	8	2	1	2	2	7	15
Vanadium	V	2	2	2	2	8	2	1	2	2	7	15
Arsenic	As	2	2	2	2	8	2	1	2	1	6	14
Boron	B	2	2	2	2	8	2	1	2	1	6	14
Copper	Cu	3	1	2	1	7	2	1	2	2	7	14
Feldspar		2	1	3	1	7	2	1	2	2	7	14

Kaolin		2	1	2	1	6	2	2	2	2	8	14
Magnesium	Mg	2	2	2	2	8	2	1	2	1	6	14
Manganese	Mn	2	1	2	1	6	1	3	2	2	8	14
Perlite		2	2	2	2	8	2	1	1	2	6	14
Selenium	Se	2	2	2	2	8	2	1	2	1	6	14
Titanium	Ti	2	2	1	2	7	2	1	2	2	7	14
Vermiculite		2	2	2	2	8	2	1	1	2	6	14
Zinc	Zn	3	2	2	2	9	2	1	1	1	5	14
Silicon	Si	2	2	2	2	8	1	1	2	1	5	13
Zirconium	Zr	2	2	1	2	7	1	1	2	2	6	13
Iron & Steel	Fe	1	2	2	2	7	1	1	1	1	4	11

From the Table 4.1, there are 3 different colours in material row. The green colour is the PGMs, yellow colour is Rare Earth Element material and white colour is basic material group.

From Table 4.1, there is 2 dimensions used to evaluate the material security and criticality, which were supply risk and material risk. While there are 4 different indicators for each dimension to determine the score for supply risk and material risk.

For supply risk, the indicators are:

a) Scarcity
b) Monopoly supply
c) Political stability
d) Vulnerability to climate change

For material risk, the indicators are:

a) Malaysia’s consumption level
b) Substitutability
c) Global warming potential
d) Total material requirements

4.1.1 Scarcity

Material scarcity is about the shortages in raw materials which are expected in the coming decades. With the growth of world population, the demand for products increasing and at the same time the demand for raw material also increase. The material scarcity is evaluate based on the scarcity paradigm that shows in research Kooroshy (2009). In the research, the material scarcity is determined by the years of extraction until exhaustion.

From the result for material scarcity, the indicators is using the source from (Halada et al., 2008). In this research, the data for material scarcity is evaluated from the relation between cumulative demand and existing reserves by 2050. For example, Palladium (Pd) is expected to overrun reserve base by 2050, so the score for scarcity for Palladium is 3 according to arrow shown in Figure 4.1.

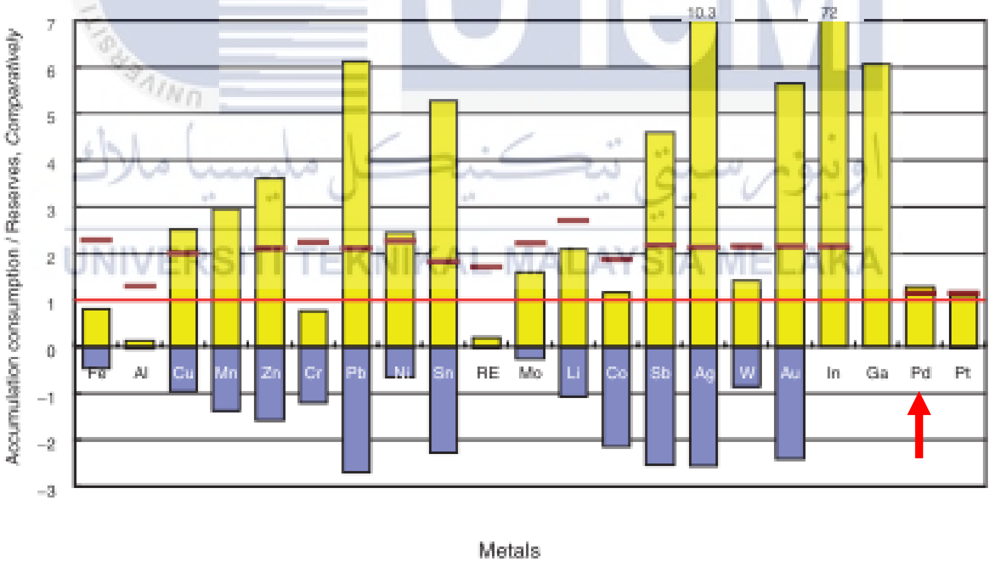


Figure 4. 1 Relation between cumulative demand and existing reserves by 2050.

4.1.2 Monopoly supply

Monopoly supply was a metric adopted by most of the studies as a clear indicator of potential material supply restriction. When there is certain material is concentrated in just one or two countries can cause the vulnerability of future supply (Hollins, 2008). Monopoly supply can be more concerned when the production of the material is only concentrated in less stable region and country.

For the indicator monopoly supply, the data is collected from Malaysian mineral Yearbook 2013 (Shari Ismail, Zulkipli Che Kasim, 2014). In the Mineral Yearbook, it contains the data about the production of material in whole world. For example, Niobium (Nb), there us 88.76% of production of Niobium is concentrate in Brazil, hence for monopoly supply, score 3 is given to Niobium due to more than 66.6% of production is concentrated in Brazil. The Table 4.2 is the world mine production of Niobium in 2013 (Shari Ismail, Zulkipli Che Kasim, 2014).

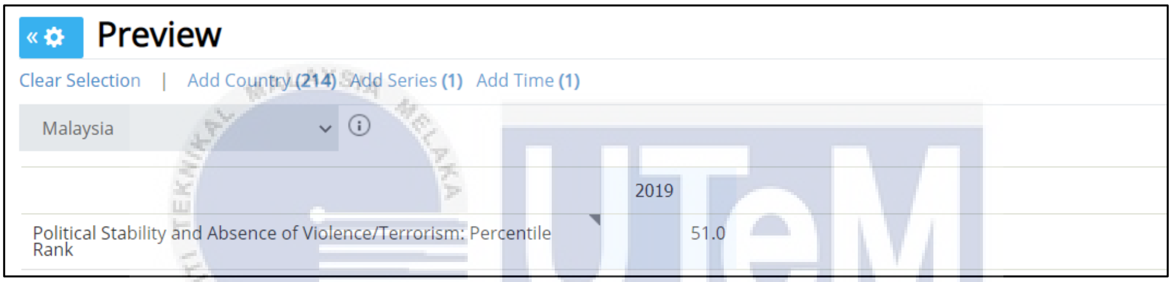
Table 4. 2 World mine production of Niobium in 2013

Country	**Tonnes**		**Percentage in 2013 (%)**
	2012	2013	
Niobium			
Brazil	45000	45000	88.76
Canada	4710	5000	9.86
Other countries	375	700	1.38
World total	50100	51000	

4.1.3 Political stability

Political stability used as indicator because political factors can exacerbate risks for future supply-chain bottlenecks. If a certain material is significantly concentrated in a low stability country, a range of political dynamics can potentially affect markets. Political instability or internal conflicts in a major supplying country can reduce or disrupt the production and mining of the material.

For political stability, the indicator is evaluated from database that publicly available from The World Bank (The World Bank, n.d.). The website provides percentile rank data for every countries and territories on various criteria including “Political Stability and absence of violence/terrorism”. For Malaysia, the percentage of political stability is 51.0% in 2019. So, for the material that monopolise by Malaysia can get score 2 for indicator political stability. The Figure 4.2 shows the result from the website.



Malaysia

	2019
Political Stability and Absence of Violence/Terrorism: Percentile Rank	51.0

Figure 4. 2 Political stability Percentile in Malaysia

4.1.4 Vulnerability to climate change

Similar to political stability, the climate change factor can also influence the supply and production of a material. Some regions and countries can be more vulnerable to the effects of climate change than others.

For indicator vulnerability to climate change, the vulnerability is evaluated from Climate Risk Index 2020 (Eckstein et al., 2020). The climate risk index used to determine what extent countries have been affected by the impacts of weather-related loss events like floods, heat wave, storms etc. For Niobium, the score for vulnerability to climate change is one because Brazil is located at low climate risk zone. The Figure 4.3 shows the global climate risk index 2020 and the circled area is Brazil.

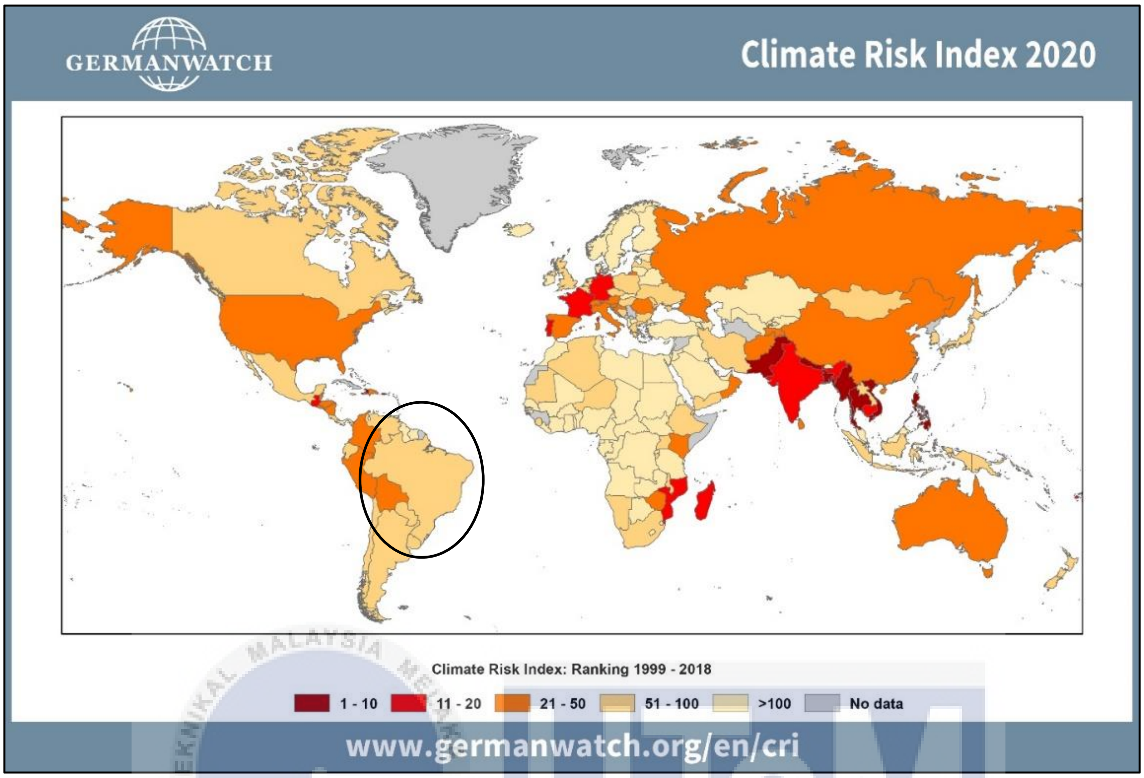


Figure 4. 3 Global Climate Risk Index 2020 (Eckstein Et Al., 2020)

4.1.5 Malaysia's consumption level

Malaysia's consumption level is the total production of materials in Malaysia. The main source of production is from mining process.

For Malaysia's consumption level, the data is collected from Malaysian Mineral Yearbook 2013 again. The Mineral Yearbook provide data for total production of material in Malaysia. For Niobium, the score for indicators Malaysia's consumption level is 1 because the production of Niobium in Malaysia is less than 1000 tonnes per year. The Table 4.3 shows the example of total production of some material in Malaysia. Struverite is a mineral that able to extract Niobium.

Table 4. 3 Total production of material in Malaysia (Malaysian Mineral Yearbook 2013)

Mineral	**2012**	**2013**
	Tonnes	tonnes
Struverite	262	190
Manganese	1,099,585	1,125,127
Silver	1,627,711	360,828
Iron	10,866,022	12,134,258
Gold`	4,624,987	3,822,708
Tin	3,275	3,697
Feldspar	482,906	314,399

4.1.6 Substitutability

Substitutability is importance in determine the supply risk of a material and it has impact on the vulnerability. The presence of a substitute can reduce the supplier's market influence. Furthermore, the supply risk of a material can reduce when there is another material which is abundant and cheap (Gupta et al., 2016). The evaluation of material substitutability is referred to other studies and research. A material is considered as high substitutability when it can easily substitute or replace by other materials. For example, copper, able to substitute by aluminium.

For indicator substitutability, the information is get Mineral Commodity Summaries 2020. In the from Mineral Commodity Summaries 2020, it contains the latest data for substitutes certain material. For Niobium, the score for indicator substitutability is 3 because there are no available substitutes for Niobium that able to perform the same performance likes Niobium. The Mineral Commodity Summaries 2020 had mentioned that the material such as molybdenum and tantalum can be substituted for Niobium, but it may have performance and efficiency loss.

4.1.7 Global Warming Potential (GWP)

Global Warming Potential (GWP) would serve as indicator in assessing the relation between global warming potential and total material requirements in regards to the selected minerals (Kosai & Yamasue, 2019). Niobium as the example, the overall score of 2 is given for global warming potential. The justification for this is based on the data correlation analysis that can be referred to Figure 4.4, where the global warming potential for Niobium identified between 1 to 100 kg CO2/kg. From Figure 4.4, the materials with higher GWP are also the ones with higher TMR. This is because for material with large TMR, means it required large amount of energy during mining process. Hence, this result in a large GWP (Kosai & Yamasue, 2019).

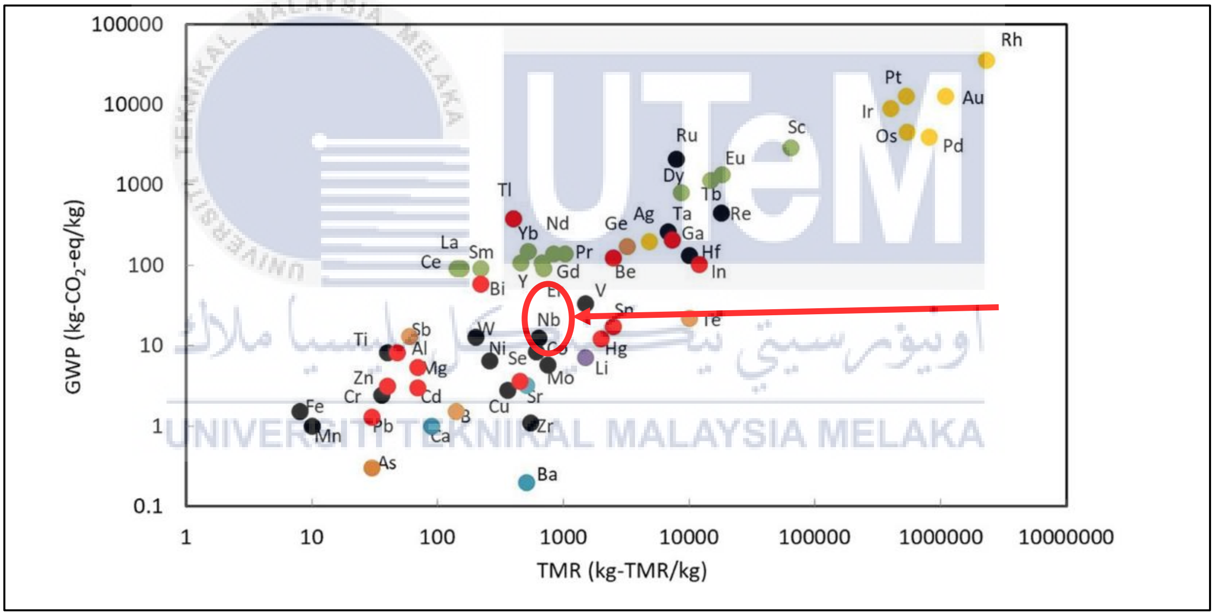


Figure 4. 4 Relation GWP and TMR (Kosai & Yamasue, 2019)

4.1.8 Total Material Requirements (TMR)

Total material requirements is the total weight of other substrate which need to be mined in order to obtain a given weight of material (Hollins, 2008). For Total material requirements, the data is assessed from which was referred to the research finding of Halada et al., (2008). This data was taken as input for assessing the total material requirements for extracting a range of material. Taking Niobium as the example, the total material requirement score was given as two. The reason for given score two is because from the Figure 4.5, the total material requirement for Niobium is around 100 tonnes/tonnes mineral, which the score 2 is given when the TMR of material is between 100 to 10000 tonnes/tonnes mineral.

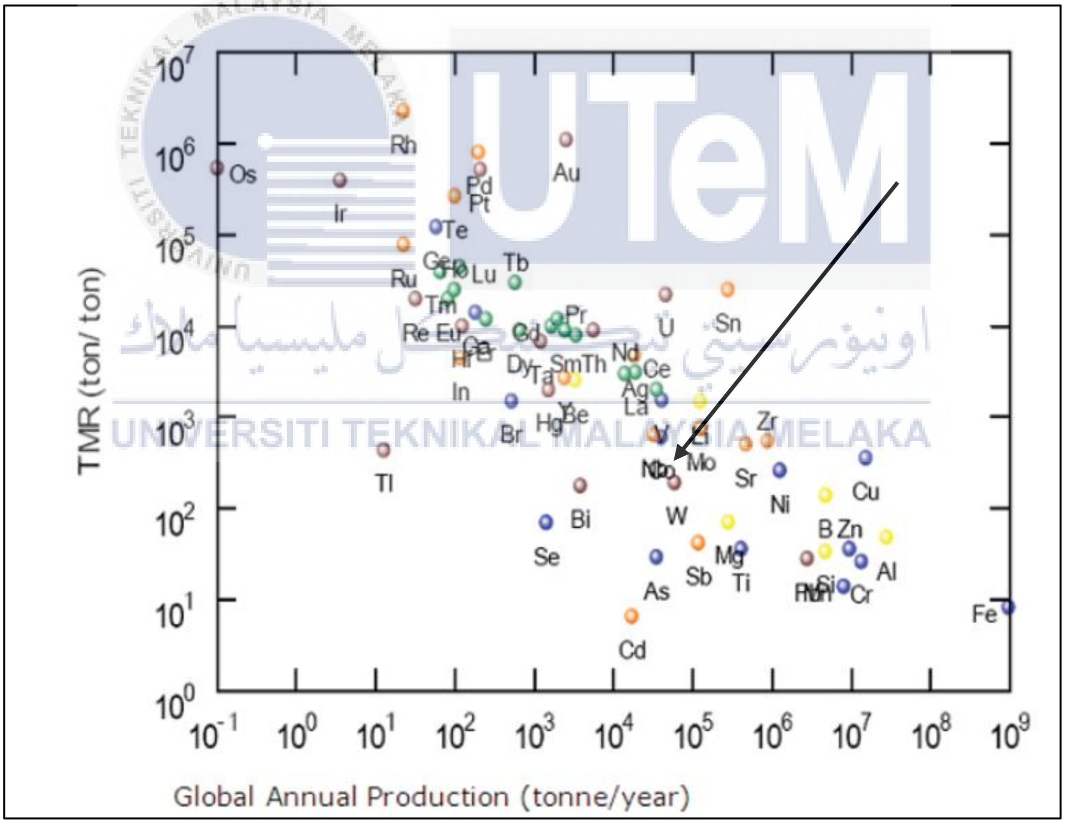


Figure 4. 5 TMR For Extracting A Range Of Material (Hollins, 2008)

4.2 Material Security Matrix

The material security matrix is the scatter graph that plotted by the data from Table 4.1. The X-axis is material risk while the Y-axis is the supply risk. The Figure 4.6 shows the material security matrix for this project. After the 89 materials were evaluated and scored based on the 8 indicators, each material had a value for material risk and supply risk. Then the materials plotted on the material security matrix.

The scatter graph was plotted by using software MATLAB R2014b. The median scores of each axis (on a scale of 5 to 11, 8 for material risk and 8 for supply risk) are taken as indicative reference points to determine the level of criticality of the materials and to categorise the materials into four zones as follows:

a) Zone 1: high material risk and high supply risk (most critical)
b) Zone 2: low material risk and high supply risk (moderately critical)
c) Zone 3: low material risk and low supply risk (least critical)
d) Zone 4: high material risk and low supply risk (moderately critical)

From the Figure 4.6, the red shaded area is most critical zone while yellow shaded area is least critical zone.

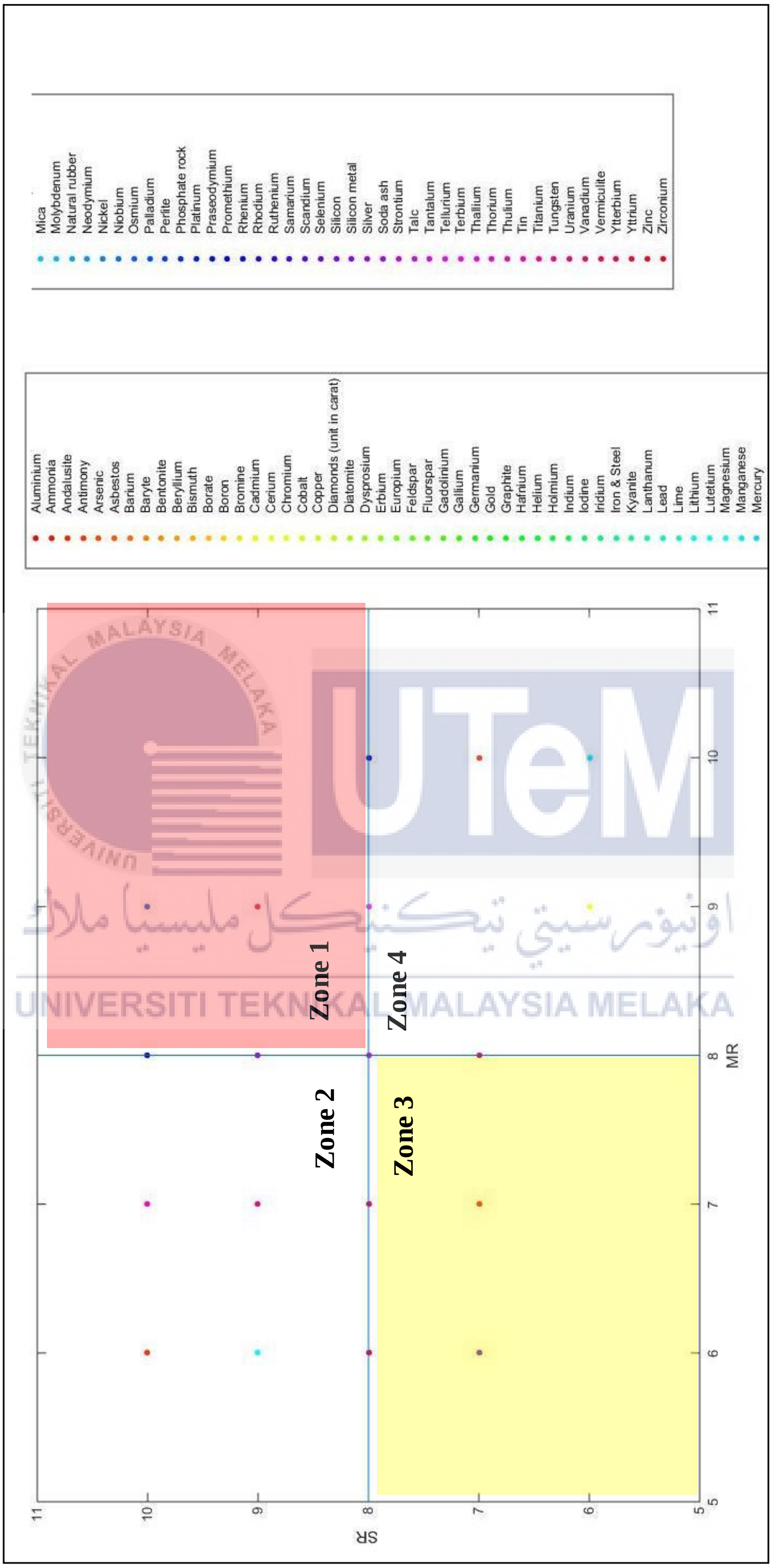
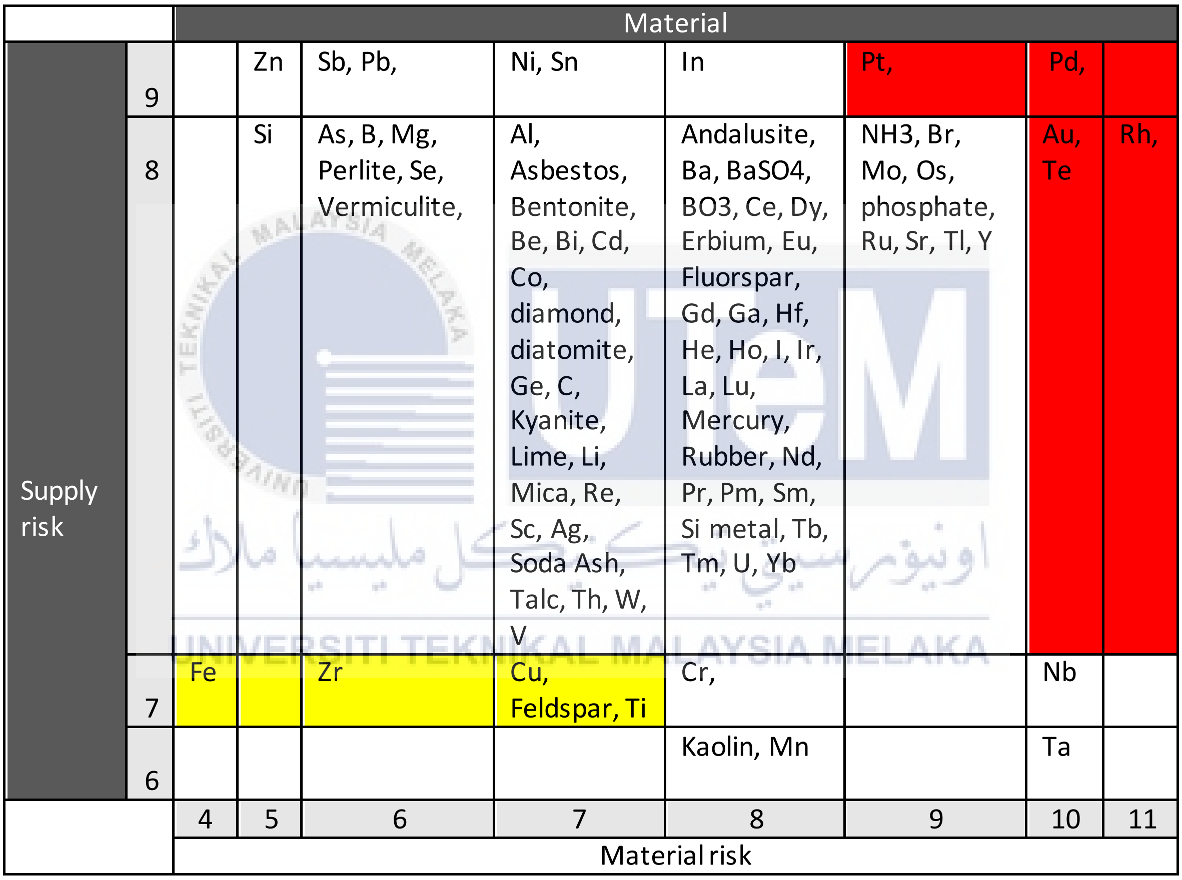


Figure 4. 6 Material security matrix

Next, the Table 4.4 shows the other pattern of material security matrix. It shows the name of materials in material security matrix. From the figure 4.10, there are 5 material is labelled as most critical material. The materials are Palladium, Rhodium, Platinum, Gold and Tellurium. Among this 5 materials, Palladium and Platinum is known as platinum-group metals. Then there are 5 materials that labelled as least critical materials, which are Iron, Zirconium, Copper, Feldspar and Titanium.

Table 4. 4 Material security matrix with material name



		Material							
Supply risk	9		Zn	Sb, Pb,	Ni, Sn	In	Pt,	Pd,	
	8		Si	As, B, Mg, Perlite, Se, Vermiculite,	Al, Asbestos, Bentonite, Be, Bi, Cd, Co, diamond, diatomite, Ge, C, Kyanite, Lime, Li, Mica, Re, Sc, Ag, Soda Ash, Talc, Th, W, V	Andalusite, Ba, BaSO4, BO3, Ce, Dy, Erbium, Eu, Fluorspar, Gd, Ga, Hf, He, Ho, I, Ir, La, Lu, Mercury, Rubber, Nd, Pr, Pm, Sm, Si metal, Tb, Tm, U, Yb	NH3, Br, Mo, Os, phosphate, Ru, Sr, Tl, Y	Au, Te	Rh,
	7	Fe		Zr	Cu, Feldspar, Ti	Cr,		Nb	
	6					Kaolin, Mn		Ta	
		4	5	6	7	8	9	10	11
		Material risk							

The Table 4.5 shows the main function and important of the 10 most critical material in sector manufacturing and industry. The source of information is from (Royal Society Of Chemistry , n.d.)

Table 4. 5 Function and important of the most critical material in different sectors.

No	Material	Sector	Function and important
1	**Palladium**	Electric and electronic	• Used as an alternating plating material to gold for connectors as it has low density and less weight of material is needed for a coating of similar thickness. • Used as fuel cells in electronic products.
2	**Rhodium**	Automotive	• Major use in catalytic converters for cars. • It can reduce nitrogen oxides in exhaust gases.
3	**Platinum**	Automotive	• Used as catalytic converters for cars. • It is effective at converting emissions from vehicle's engine into less harmful waste products.
		Electric and electronics	• Used in thermocouples that can measure temperature in the glass, steel and semiconductor industries.
4	**Gold**	Jewellery	• Used extensively in jewellery, either in pure form or as an alloy. • Used as decoration.
		Electric and electronic	• Gold is a metal that is highly efficient conductor that can carry very tiny currents and remain free of corrosion. • Used in connectors, and switch for electronic device like smartphone, laptops, calculator etc.
5	**Tellurium**	Mechanical	• Normally used as additive to others metal like copper and stainless steel to improve its machinability.
		Oil and gas	• Used as a catalyst in oil refining.
		Electric and electronic	• Doped with silver and gold in semiconductor applications. • Used in rewriteable CD and DVDs.

6	**Ammonia**	Agriculture	- Used in agriculture as fertilizer.
		Household products	- Ammonia is very effective at breakdown household grime and strains such as cooking grease.
		Industrial	- Used as refrigerant gas in air-conditioning equipment to absorb heats from its surroundings.
7	**Bromine**	Electric and electronic	- Used as flame retardants for electronic casing to make them less flammable.
		Safety	- Bromine can used in halon fire extinguishers that are used to fight fires in places like aeroplanes and tanks.
8	**Indium**	Electric and electronic	- Material that is an important part of touch screens and solar panels. - This is because it can conduct electricity and bonds strongly to glass and its is transparent. - Indium also used widely in semiconductors as transistors and microchips.
		Automotive	- Used as coating for ball bearing in Formula 1 racing cars due to its low friction.
9	**Molybdenum**	Automotive	- Used in parts of engines to increase strength, hardness, and electrical conductivity.
		Oil and gas	- Used as catalysts for petroleum industry.
10	**Niobium**	Aerospace	- Used in jet engines and rockets to improve its strength.
		Optical	- Can added to glass to increase the refractive index and allows corrective glasses to be made with thinner lenses.

4.2.1 Material security index in various countries

There are numerous countries that have carried out research on material security and criticality in current studies, such as India, the EU, the UK, Australia and Japan. The dimensions and indicators used by each country is different, so the list of material security in each country is also different. Table 4.6 shows the ranking of material security in various countries. Table 4.6 shows similar lists of material security commodities in varies countries. From the Table 4.6, shows that platinum-group metals and rare earth elements has higher ranking in many countries include Malaysia. This means these materials are important to the industries and economy growth in a country. Nowadays platinum-group metal is mainly used as catalytic converters in industries while rare earth elements is important in development of high technology products and renewable energy.

There is a relationship between the ranking of material security and the value of products in a country. In Japan, the highest percentage of export product in Japan is vehicles, which is up to 21.1% of total export, hence the raw materials that are high value in automotive sector will locate higher rank in material security database Japan (Workman, 2019). For example, neodymium and lanthanum magnets used in electric motors and neodymium had the highest rank in material security Japan (Green Car Congress, 2018). For Malaysia, the electrical machinery and equipment contribute the 34.4% of total exports, which is the highest percentage of total exports (Workman, 2019). So, the materials such as Palladium and gold which are valuable in E&E sector located in higher ranking of material security Malaysia. In summary, the higher the value of material to a country, the higher the ranking of material in material security database.

Table 4. 6 Ranking of material security in various countries

Ranking	Malaysia	UK	EU	India	Australia	Japan
1	Palladium	Gold	Dysprosium	Strontium	Gallium	Neodymium
2	Rhodium	Rhodium	Magnesium	Phosphate	Indium	Dysprosium
3	Gold	Mercury	Samarium	Potash	Tungsten	Indium
4	Platinum	Platinum	Gadolinium	Vanadium	Cobalt	Niobium
5	Tellurium	Strontium	Rhodium	Boron	Niobium	Tin
6	Ammonia	Silver	Tungsten	Barium	Manganese	Silver
7	Bromine	Antimony	Neodymium	Lithium	Molybdenum	Zinc
8	Indium	tin	Cerium	Chromium	Antimony	Tantalum
9	Molybdenum	Magnesium	Holmium	Molybdenum	Lithium	Manganese

10	Niobium	Tungsten	Lutetium	Silicon	Vanadium	Cobalt
11	Osmium	Baryte	Terbium	Niobium	Nickel	Gold
12	Phosphate rock	Talc	Thulium	Cobalt	Tantalum	Platinum
13	Ruthenium	Bismuth	Ytterbium	Limestone	Terbium	Iron
14	Strontium	Palladium	Antimony	Selenium	Chromium	Rhodium
15	Thallium	Nickel	Phosphorus	Antimony	Selenium	Palladium
16	Yttrium	Boron	Niobium	Gypsum	Titanium	Lead
17	Andalusite	Andalusite	Erbium	Nickel	Strontium	Copper
18	Barium	Molybdenum	Cobalt	Bentonite	Graphite	Chromium
19	Baryte	Zinc	Palladium	Germanium	Tin	Molybdenum
20	Borate	Holmium	Bismuth	Graphite	Germanium	Tungsten

4.3 The Application of the Malaysia’s Material Security Database for the Product Recycling Desirability

After the development of database of material security, then the material security can used as one of the parameters for Product Recycling Desirability Model for Malaysia. For the calculation for material security desirability, the formula is:

$$\sum_{i=1}^{n}\left(\frac{MiSi}{MTStop}\right) \qquad \text{equation 4. 1}$$

M_i is mass of material in a product, M_T is the total mass of material. S_i is the material security index of the material, while S_{top} is the top scale for the material security index. In this project, the top scale of material security index is 24.

Example, the details of calculation for refrigerator shown below:

Refrigerator:

$$D_{msi\text{-}iron} = \frac{5.4\times11}{99.8\times24} = 0.0248$$

$$D_{msi\text{-}copper} = \frac{3.12 \times 14}{99.8 \times 24} = 0.0182$$

$$D_{msi\text{-}zinc} = \frac{0.08 \times 14}{99.8 \times 24} = 0.000467$$

$$D_{MSI\ refrigerator} = (0.0248 + 0.0182 + 0.000467) = 0.0435$$

The Table 4.7 is the product recycling desirability index for different products. There are 7 different products is selected to determine its recycling desirability. For the value for parameters simplicity and technology readiness desirability, the value is used from previous study, only the material security desirability is used the input from Table 4.1.

Table 4. 7 Product recycling desirability index for Malaysia

Product	**Simplicity**	**Material Security Desirability**	**Technology Readiness Desirability**	**Total Recycling Desirability Index**	**Total Virgin Material Value (RM)**
Car battery	0.64	0.409	1.00	2.049	309.67
DVD-R (50piece)	0.51	0.348	1.00	1.858	60.17
Smartphone	0.38	0.466	1.00	1.846	550.75
Desktop computer	0.25	0.469	1.00	1.719	1550.93
Wind turbine 100kW	0.78	0.002	0.9	1.682	238921.55
Refrigerator	0.51	0.0435	1.00	1.554	1911.89
Coffee maker	0.52	0.014	1.00	1.534	12.188

4.3.1 Product distribution graph

Product distribution graph is an analysis to prioritize the products for recycling. Product distribution graph for current project is shown in Figure 4.7. While Figure 4.8 is the product distribution graph for previous study, also known as Gutowski Complexity Graph. The different between the 2 graphs are for Figure 4.7, the product that has higher total recycling desirability index will give priority to recycle. But for Figure 4.8, the priority to recycle is given to product that has lower simplicity value.

From Figure 4.7, the product in top right of the graph is the most important product for recycling because the products that are high recycling desirability index and high material value is located at top right corner. The rating for recycling based on Figure 4.7 is car battery, DVD-R, smartphone, desktop computer, wind turbine, refrigerator and coffee maker. While from Figure 4.8, the rating for recycling is desktop computer, smartphone, refrigerator, DVD-R, coffee maker, car battery and wind turbine.

In summary, the result from Figure 4.8 is only focus on physical disassembly but for Figure 4.7, it is using more factors and parameters which is more preferred by industries due to more parameters used to obtain the result.

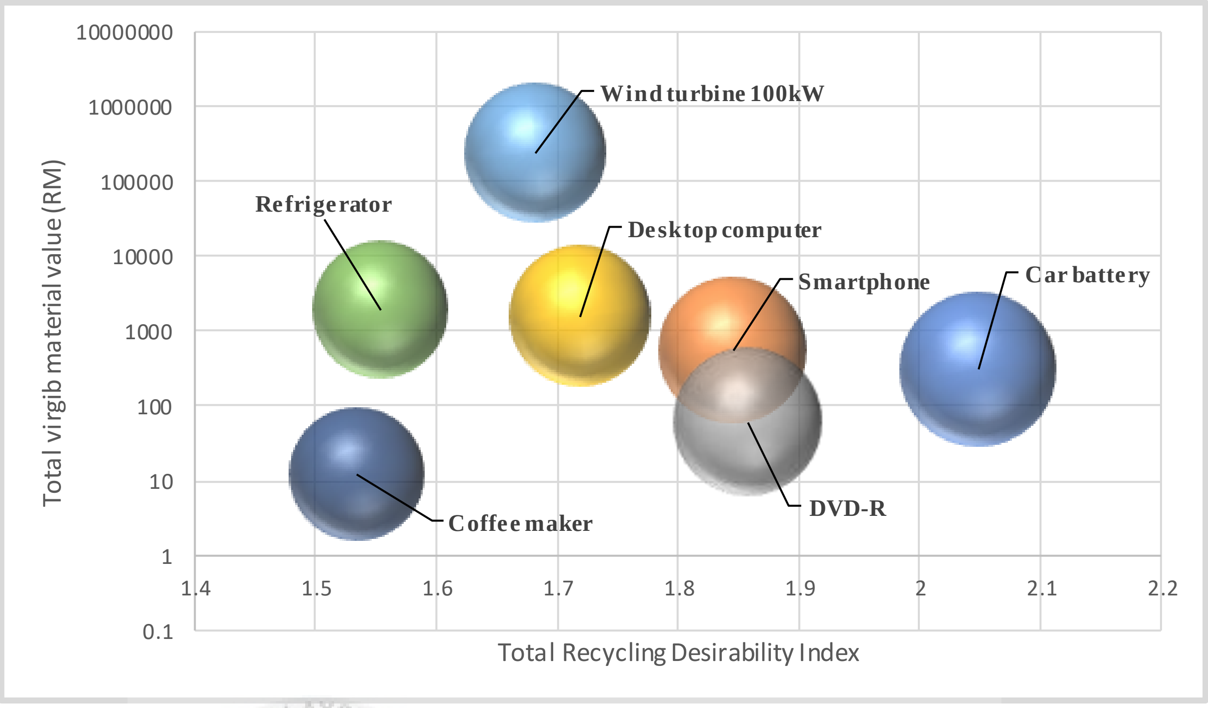


Figure 4. 7 Product Distribution Graph

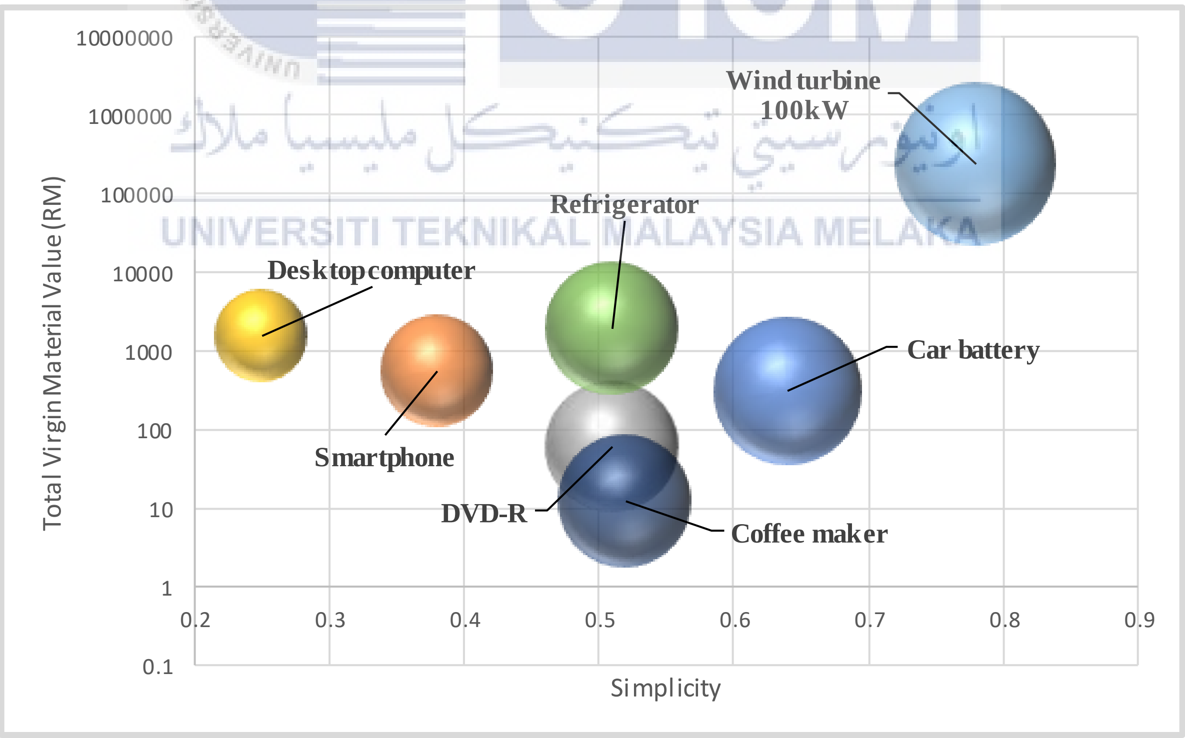


Figure 4. 8 Gutowski Complexity Graph

CHAPTER 5

CONCLUSION AND RECOMMENDATION

This chapter concludes the research on development of the material security database for Malaysia assisting the Product Recycling Desirability Model. The conclusion is made from the objectives of the project.

5.1 Conclusion

In conclusion, this project has developed a material security database for Malaysia to assist the Product Recycling Desirability Model. The 2-Dimensional material security matrix adopted to evaluate the material security. The dimensions used are material risks and supply risks. There is total 8 different indicators used to develop the material security database, which is material scarcity, monopoly supply, political stability, vulnerability to climate change, Malaysia consumption level, substitutability, global warming potential and total material requirements. From this project, most of the precious material such as platinum-group metals and rare earth elements were categorized as critical material and have higher ranking in material security database. This kind of materials also important in varies sectors industry and manufacturing such as electric and electronics, automotive, aerospace and renewable energy.

While the development of material security database can help to construct Product Recycling Desirability Model. There are three parameters needed to make Product Recycling

Desirability Model applicable to Malaysia. The parameters are product complexity index, technology readiness level and material security index. Then the Product Recycling Desirability Model can help to evaluate material recycling desirability of different products such as car battery, smartphone, DVD-R, refrigerator etc. A product is important to be recycled when the product has a high index in product recycling desirability. By establishing the critical material list for Malaysia economy, the recycling initiatives can be strategically implemented by the government including applying the Product Recycling Desirability Model, as the MSI for Malaysia is now ready.

5.2 Recommendations

After gone through this research, there are some recommendations suggested to improve this study in future. The recommendation for this project is focus on the improving for the quality of the data. The following points could be considered to increase the quality of data:

- Conducting more research on the selection of indicators used for the material security database.
- Collecting more information and data for selected materials to improve the accuracy of material security database.
- Continuous consultation with industry stakeholders as they can provide useful insight and feedback that are not necessarily available through existing data sources.

5.3 Sustainability Element

Based on the material security database developed in this project, the data and results obtained can contribute to the improving material and resource efficiency. It can maximize the value of material along its life cycle especially for precious material such as rare earth elements and platinum-group metals. Moreover, the results of this project can increase the material conservation, such as recycle and recover the material from waste products, develop the technologies for recovering secondary materials from primary material processing activities and reduce the environmental impacts from mining process.

5.4 Lifelong Learning Element

During the assessment of this project, the knowledge obtained was the method to develop material security database and construct Product Recycling Desirability Model for Malaysia. The knowledges and skills learned thru this assessment are selecting the suitable indicators and parameters to evaluate material security and criticality, plot the material security matrix by MATLAB and construct the product distribution graph. These knowledges and skills will be useful in future research for improvement in recycling field.

5.5 Complexity Element

The complexity element in this project is the selection of parameters used to evaluate material security. The parameters used to evaluate material security can affected the accuracy of material security database for Malaysia. From current research, there are many parameters and indicators used by different researchers from each country. This is because the purpose and aim of each country to develop material security database is different. Therefore, there is must for researcher to analyse and select parameters used for material security database properly.

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